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Article

The Wickedness and Complexity of Decision Making in Geoengineering

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Abstract: Geoengineering, the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change, has been more widely considered as an accompanying strategy to conventional climate change mitigation measures to combat global warming. However, this approach is far from achieving agreements from different institutional domains. Geoengineering, intended to be deployed on a planetary scale, would cause fundamental interventions to the human-environment system and create new risks and problems with high uncertainty and uneven distribution around the globe. Apart from the physical effects, conflicting attitudes appear from social, economic, and environmental worldviews in the international community. The intertwined sociotechnical complexity and conflicting attitudes make geoengineering a wicked and complex issue. This article elaborates the wickedness and complexity from a system perspective, primarily for an interdisciplinary, policy-oriented audience.

Keywords: geoengineering; earth system; human-environment system; interventions; feedback loops; wickedness; complexity; decision making

1. Introduction

Climate change and sustainable development are in a dual relationship. On one hand, climate change influences human living conditions, ecosystems, and its services, thereby also the life-supporting system for social and economic development. On the other hand, different societal interpretations and agendas for sustainable development influence both the Green House Gas (GHG) emission that causes climate change and the vulnerability of nature and society within various contexts. Global environmental changes reshape the interaction between people and their environment in human-environment systems. Climate change is a global systemic change that influences production and consumption, land use change, industrial development, and other human activities. However, the impact of climate change is unevenly distributed worldwide, with developing countries and poor regions being the most vulnerable [1,2]—in part because of their geographical location, their poor coping capacity, and the vulnerability of social, economic, and institutional systems [3]. The increasingly frequent extreme climatic events cause severe damages to both developed and developing countries. Stakeholders from various societal contexts in different parts of the world hold different climate impact interpretations. In order to limit the climate change impact within the planetary boundary [4], convergence on decarbonization in the international community is needed so that countries work toward mitigation targets that are in their self-interests as well as in the interests of all. Future projections indicate that technological innovations and institutional regulations are needed for mitigation and adaptation to prevent dangerous climate change [5].

Climate policy in recent decades has been mainly focused on reducing the anthropogenic greenhouse gas emissions to the atmosphere. The direct and indirect causes of climate change are considered multifold and interlinked. GHGs and land use change are main drivers of climate change. Anthropogenic activities accelerate the change of the climate system [2]. The concentration of the major greenhouse gas, carbon dioxide, increased from 278 part per million (ppm) before industrialization to over 400 ppm in 2013. Other greenhouse gases that have higher global warming potential, CH_4 and N_2O also manifested an increase by a factor 2.5 and 1.2, respectively, since preindustrial times [6,7]. The United Nations Framework Convention on Climate Change stated, as early as 1992, a global objective of stabilizing greenhouse gas concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system". It has been widely suggested that the global temperature should be limited to a 2 °C increase compared to pre-industrialization [8]. However, projections still show a 20% likelihood toward a 4 °C rise by 2100 [9], depending on both the emissions scenario and uncertainty in the climate response to those emissions. Research has projected that the 4 °C scenario will lead to a sea-level rise of 0.5 to 1 meter and cause a 150% increase of ocean acidification [9]. Concurrent threats in the 4 °C scenario include exacerbated water scarcity, more frequent extreme events, dramatic loss of biodiversity, monsoon system intervention, deterioration of ecosystems and associated services, *etc.* These impacts are revealed under high uncertainty and nonlinear states. It's suggested that the 4 °C scenario is likely to cause severe ecological damages with unequal geographical distribution around the world. To avoid dangerous climate change, it's suggested that future economic and technological effort is needed to hold global warming below 2 °C [9]. Notwithstanding these policies emerging, inadequate collective effort from the international community toward substantive mitigation of CO_2 emission, coupled by recent evidence of accelerating climate change [10], has fuelled intensive research on a potential third option of combating global warming, alongside mitigation and adaptation. Geoengineering, also referred to as "climate engineering", has emerged as such potential third option, sometimes considered as a stopgap "end-of-the-chimney fix" to be used in case of a "climate emergency" or a "quick-fix" to temperature rise in order to "buy time" for decarbonizing the economy [8,9,11,12], though some think that it should be combined with mitigation rather than used separately [13]. Nevertheless, while causing significant discussion, geoengineering remains controversial [14]. Debates on geoengineering could be found among natural scientists, social scientists, philosophers as well as policy makers. Such controversies are not only about whether geoengineering should be deployed today or in the future but also whether it is necessary to carry out large-scale research into such intentional climate manipulation alternative [15], evidenced by the "arm the future argument" [16] and its opponents. Moreover, from the psychological point of view, how geoengineering could be framed through the use of conceptual and discourse metaphors, could also influence the decision-making and public attitude. Metaphors such as "geoengineering as a techno-fix", "geoengineering as a medical fix", "geoengineering as Plan B", "metaphors and arguments of discontent" have been systematically evaluated in [17].

The Royal Society defined "geoengineering" in a September 2009 report as "deliberate large-scale manipulation of planetary environment to counteract anthropogenic climate change" [18]. Geoengineering is considered a catchall term for a bunch of technologies countering anthropogenic climate forcing. The report categorized two groups of technologies under the definition of geoengineering: Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR). Both SRM and CDR aimed at cooling the earth. However, SRM acts in the shortwave of the spectrum and therefore deals with symptoms of global warming, while CDR acts in the long-wave part of the spectrum, thus eradicating the root causes of climate change. According to the Royal Society report (2009), SRM approaches include (1) increasing the surface reflectivity of the planet, by brightening human structures (e.g., by painting them white), planting of crops with a high reflectivity, or covering deserts with reflective material); (2) enhancement of marine cloud reflectivity; (3) mimicking the effects of volcanic eruptions by injecting sulphate aerosols into the lower stratosphere; and (4) placing shields or deflectors in space to reduce the amount of solar energy reaching the earth. And CDR approaches include (1) land use management to protect or enhance land carbon sinks; (2) the use of biomass for carbon sequestration as well as a carbon neutral energy source; (3) enhancement of natural weathering processes to remove CO_2 from the atmosphere; (4) direct engineered capture of CO_2 from ambient air; and (5) the enhancement of oceanic uptake of CO_2, for example, by fertilization of the oceans with naturally scarce nutrients or by increasing upwelling processes [18]. Among all these methods, both Royal Society and Novim Group distinguished two SRM techniques as the most promising for research: shooting sulphate aerosols into the stratosphere in order to deflect the sun's light and heat and increasing albedo of marine clouds [19].

Geoengineering the climate is a salient manifestation of a wicked and complex issue that transcends the boundaries between science, ethics, politics, economy, culture, and environment. This kind of problem is generally regarded as a "wicked problem". The term was firstly coined by Rittel and Webber in the arena of social policy, an arena in which a purely scientific-rational approach cannot be applied because there is no consensus of the clear definition of the problem, no agreement on the relevant knowledge or the norms and values at stake due to differing perspectives of stakeholders [20]. A wicked problem is described as a problem that is difficult, if not impossible, to solve because of incomplete, contradictory, and changing requirements that are often difficult to recognize. The term "wicked" does not mean evil but rather addresses the complexity of the problem and the resistance to resolution [21].

Besides, because of the complex interdependency of various aspects of the problem, the effort to solve one aspect of the problem might raise feedbacks or side effects, creating other problems in other aspects or domains.

The earth climate is a complex adaptive system. A complex adaptive system is defined as “a dynamic network of many agents acting in parallel, constantly acting and reacting to what the other agents are doing. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents” [22]. Besides, the earth is a complex whole that contains various cycles, circulations, and balances. Different cycles have various time and geological scales. Intervention of one cycle or balance at a certain time and location could induce abrupt, chronic, or delayed crisis in other cycles or balances. Geoengineering as a planetary-scale climate manipulation will cause an intervention in the earth’s cycles and produce side effects from various domains. For such a complex adaptive system, the concurrent changes in different cycles could lead to an emerging property of substantive system change.

2. Elaboration on the Wickedness and Complexity of Geoengineering

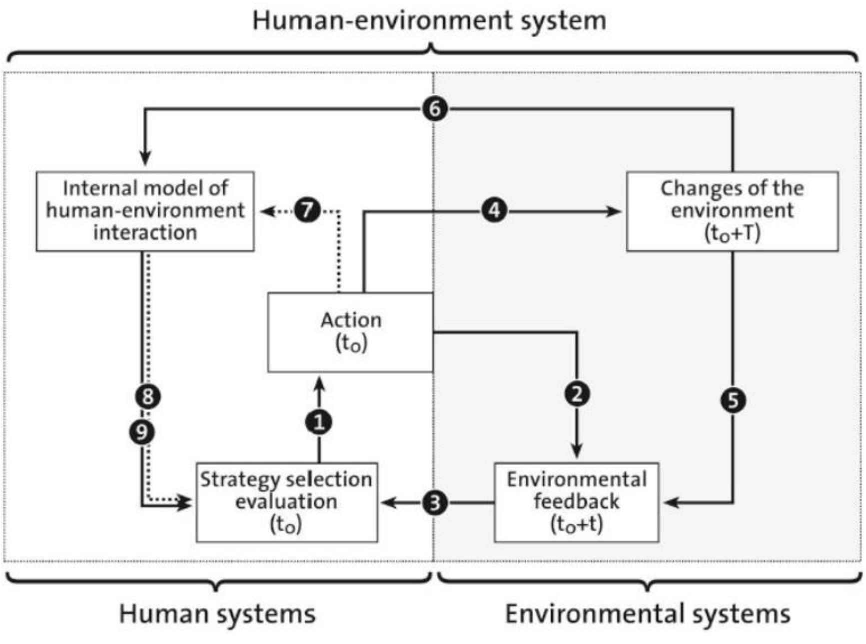
This article elaborates on the wickedness and complexity of geoengineering through six major arguments: complex cross-boundary feedbacks, economic affordability, decision-making criteria, conflicting interests and values, lack of central governance, and tuxedo fallacy of decision making. The discussion attempts to outline why geoengineering presents challenges as well as opportunities to humans and why it should be considered a “wicked” problem. The following sections discuss the relevant linkages between man and environmental systems, the difficulty of objectively assessing the success (or lack thereof) of a geoengineering intervention, the problem of conflicting interests and values, and the lack of any central governance. Therefore, decision making on geoengineering policies should take a timescale of risks perspective as well as consideration on other factors, such as costs, ethics, governance, *etc*.

2.1. An Argument on Complex Cross-Boundary Feedbacks in Human-Environment System

Human-Environment Systems (HES) are conceptualized as a coexistence of two different systems with mutual dependencies and reciprocal endorsement, capturing all environmental and technological systems that are relevant for or affected by humans [23]. It’s argued that the mutuality is not symmetric but beneficial or necessary for the existence of at least one of the two subunits of this system. Human decisions and the short- and long-term environmental impacts from the feedback loops will directly influence the evolution of the system. Detailed philosophy about the HES framework could be seen in [24]. Global and local environmental problems invoking environmental concerns could be better understood with a reexamination of HES, where social and ecological aspects are interacting at multiple temporal and spatial scales [25].

To understand the intervention of geoengineering in the climate feedback system as well as its impacts on HES, the HES framework developed by Scholz [24] is employed to facilitate the understanding of the following argument in this article for the detailed investigation of feedback loops. Figure 1 illustrates that primary and various secondary feedback loops at different timescales are included in the human-environment relationship. Human decisions at t_0 are assumed to follow the goal-oriented decision rules of the respective agents. The primary feedback of intended impacts at t_0 + t after human action at t_0 is then perceived by human agents for adaptive decision making and reactions. The inner cycle of the arrow forming loop F_1 = (1,2,3) represents the primary feedback, which is, however, coupled by various secondary feedback loops at the second order or the third order, such as F_2 (1,4,6,9) and F_3 (7,8,1). Scholz concluded that secondary feedback loops include three types: F_1, secondary feedback of unintended changes; F_2, secondary feedback loop learning; and F_3, the secondary feedback loop of self-reflection [24]. Normally, the secondary feedback loop refers to a delayed and long-term environmental impact at t_0 + T, in which T could stand for decades or even a longer time. The concept of "learning" is embedded in the HES framework, especially via the F_2, secondary feedback loop learning of substantial environmental change at large scales. Human agents learn and adapt their behavior and decision making from the evaluation and learning of impacts in the environmental system, through which humans build up their environmental consciousness. It's worthwhile to recognize that the delayed long-term environmental impacts at t_0 + T might have a dramatic negative influence on human systems, such as the result of global warming. Inspired by the theoretical foundation of the HES framework, this article borrowed the feedback loop rationale from the HES framework in the following elaboration on innovative insight of the interventions of geoengineering to bring in a "timescale of risks" concept.

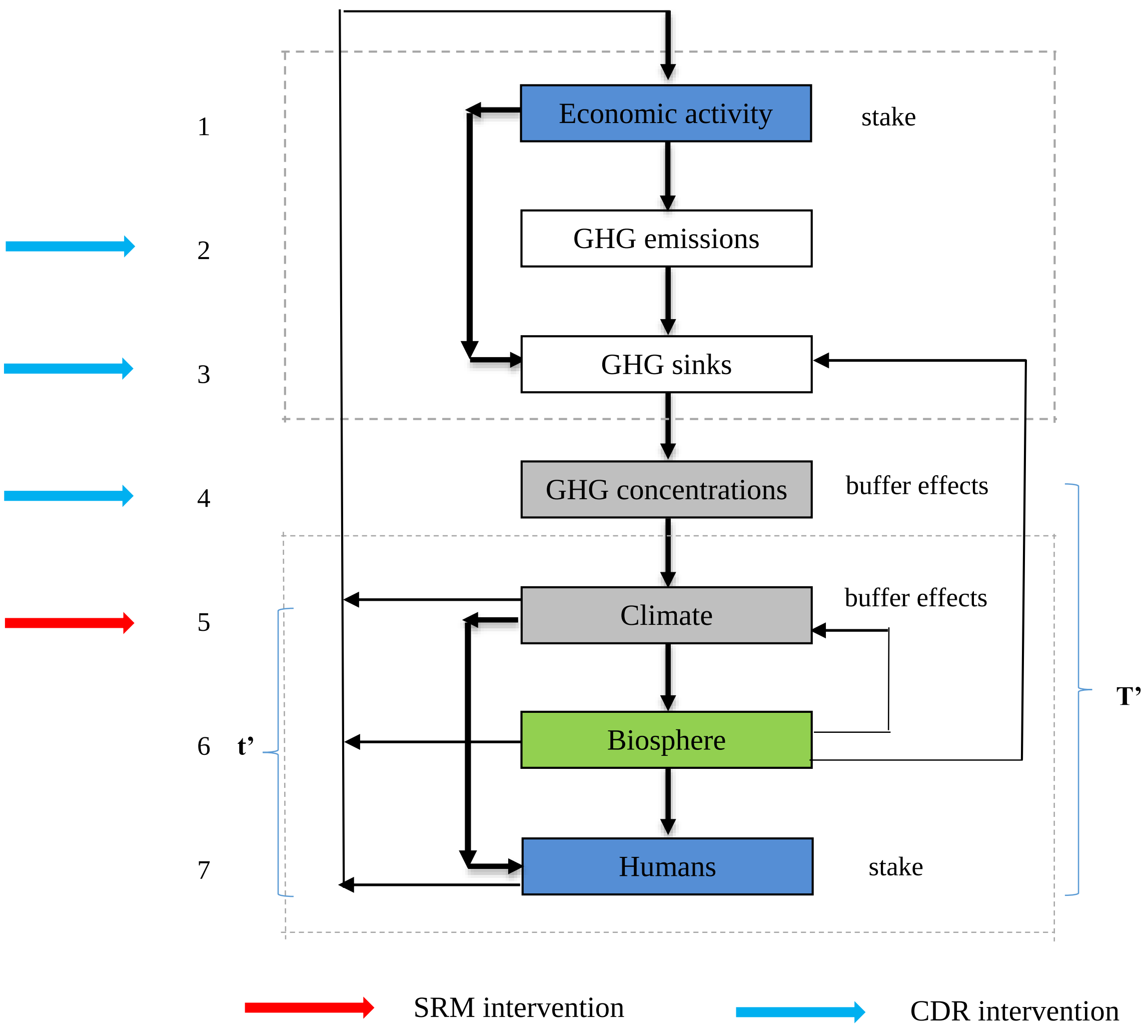
Figure 1. Primary and various types of secondary feedback loops in human-environment interaction source: Scholz [24].



The enhanced greenhouse effect possesses influences via complex feedback loops between the climate system and the biosphere and technosphere, respectively. Climate change has influences on the ecosystem and humans, further causing feedbacks via the economy.

Geoengineering, defined as "deliberate large-scale manipulation of planetary environment to counteract anthropogenic climate change", carries an inherent worldview in the anthroposphere and an implicit recognition of man itself as the executor of manipulation and also a major stakeholder, perhaps with its economy as a whole since economic activity is an essential regime of human civilization. Against the backdrop of the Anthropocentrism assumption, we might be interested to think of how geoengineering could influence humans ourselves, especially with the timescale of risk perspective. This could be diagnosed if we compare the intervention phases in the feedback system as illustrated in Figure 2. Common criticisms on SRM include the following: (1) it only deals with the symptoms of climate change, notably rising temperature, without tackling the root cause of greenhouse gas concentration in the atmosphere [26]; (2) it doesn't solve the ocean acidification problem [27,28]; (3) injecting SO_2 into the stratosphere may further cause ozone depletion [27,29,30]; (4) significant whitening of the daytime sky [31,32]; (5) increasing acid deposition [32,33]; (6) less sun for solar power [31] *etc*. These listed disadvantages of SRM are possible side effects argued in a patchwork way, from a side-effect perspective but not from the relationship of geoengineering and humans in the human-environment system.

Figure 2. Geoengineering intervention phases in the modified human-climate feedback system framework.



Our rationale here on the superiority of CDR over SRM, however, gives an alternative philosophical argument that aids our strategic decision making. It is identified by positioning the CDR and SRM interventions into the modified human-climate feedback system adapted from Common's illustration [34] for the evaluation of the "proximity of stake to catastrophe" based on a particular view of the coupled human-climate system. We define this new concept "proximity of stake to catastrophe" as "how much distance a risk stays from the stakeholder and how long it will take if a catastrophe (dramatic unintended change) happens and finally destroys the stake".

Figure 2 presents geoengineering intervention phases in our defined human-climate feedback system framework. The topological organization of the figure is based on the fundamental causality of major subsystems and major activities that influence climate change. Each box represents a subsystem in the coupled human-climate systems. Linkages between subsystems (arrows linking boxes) illustrate the direct influencing power from one subsystem to another subsystem. On the ground of the current scientific understanding of climate feedback system embedded in the biosphere and technosphere, the topological organization and the major linkages among the subsystems are fixed. One may change the positions of the boxes in the figure and reorganize the sequence of the boxes from 1 to 7, however, the major linkages of the subsystems and their influencing relationships remain the same in the context of climate change topic (the "concentrations", "sinks", "emissions" are referring to GHG). As mentioned above, in the climate manipulation feedback system illustrated in Figure 2, man and his economy are considered as the central stake. Because the SRM approaches could not change the fundamental greenhouse gas concentration, the intervention of SRM could only be recognized as working on "climate" phase (shown as box 5 in Figure 2) as it functions as a "quick aid" to cool down the temperature. SRM generally does not deal with GHG "emissions", "sinks," and "concentrations" (from box 2 to 4). Nevertheless, CDR, as its name illustrates, aims at reducing CO_2 concentration directly (box 4). The CDR approach intervention ranges from "emissions" to "sinks" to "concentrations" as a whole combination. Biofuels, renewable energy, and "end-of-chimney scrubber" are all mitigation measures to reduce CO_2 "emission" (box 2); land use management to enhance land carbon sinks and ocean fertilization to enhance algae uptake of CO_2 fall into the category of "sink" intervention (box 3); carbon capture and storage (CCS) is usually proposed as a direct action to reduce CO_2 "concentration" (box 4). By scrutinizing the system, we could find that the stake (human well-being and economy) is "with closer exposure" to the intervention at the climate itself (by SRM). As shown in Figure 2, "climate" (box 5) has direct connections (climate change influence) with "human" (box 7) and "economy" (box 1) as well as indirect connections with both via the biosphere (box 6) without buffer mechanisms. This illustrates that the action of anthropogenic climate modification at a planetary scale could have a direct influence or quick indirect influence on the major stakeholder—human being and his economy. The proximity (timescale of risk) of the intervention phase toward the stake poses high potential vulnerability to both human well-being and his economy, especially when such an intervention is deployed on a planetary scale and a remedy would be too late to compensate. The uncertainty of the SRM effect and its nature of inability in eradicating the root cause of climate change, as well as the high risk of an abrupt cease in operation due to unexpected situations (e.g., political or economic will to cease injecting aerosols), or even the irreversibility error of large-scale deployment (e.g., space mirror), could cause dramatic catastrophe to human and society due to the proximity of the action to the stake. Sudden termination of SRM geoengineering is exactly one of the concerns pertaining to whether such technologies should be deployed [35,36]; political or economic instabilities, leading to an abrupt cancelation of SRM, could severely multiply the risks of dangerous climate change (*cf.* Royal Society, 2009) [18]. Assuming the geoengineering action is taken at time t_0, the intended cooling effect should take place at $t_0 + t_1$. However, due to uncertainties and potential errors, the unintended side effects or even *catastrophe* could arrive at $t_0 + t_1 + t'$. However, CDR approaches, also called long-wave geoengineering, work on spheres of "emissions" (box 2), "sinks" (box 3), and "concentrations" (box 4) while these spheres do not have a direct connection (climate change influence) either to man or to his economy from the global warming perspective. Philosophically, it's only when these spheres influence the "climate" subsystem (box 5) that they could influence the stake subsystems ("human" and "economy") in the whole coupled human-climate system. Although we should recognize that "emissions" also lead to other types of environmental pollution and human health hazardous effects, the reasoning here only focuses on the impacts of global warming. Other types of environmental pollution impact are not within the scope of this discussion. The intervention of CDR prevails over SRM in part because it deals with the root cause of greenhouse gas concentration and in part because it has relatively less risk of causing catastrophe on human society and economy. This is due to the intervention being at the upstream of the feedback system that its impact has to diffuse chain effects through all the rest of the step-spheres (depicted by the boxes) to finally reach "human" and "economy," while the resilience in the step-spheres could offset certain impacts. Therefore, any side effect or unintended impact of the CDR intervention needs to diffuse via several step-spheres with buffer effects and thus takes longer to finally influence humans, rather than a dramatic and abrupt error impact caused by failure of SRM, for which the stake is more directly exposed to the detrimental impacts in the "climate" sphere. More importantly, from cause to effect, the "concentrations" phase stands in the middle as a buffer of time in the feedback system, particularly due to nature's self-regulating capability, resilience—sometimes called the "Gaia effect". One example of such "buffering effect" is the enhanced CO_2 uptake by plants due to elevated atmospheric CO_2 concentrations and in higher temperatures. For instance, the biomass productivity of crassulacean acid metabolism (CAM) species could reach a 35% increase in response to a doubled atmospheric CO_2 concentration [37]. This is the buffer effect of increased concentrations leading to increased sinks. On the other hand, the process is slowed down to certain extent if changes of "sinks" result in radical changes in "concentrations" and subsequent "climate". However, after "climate", the stakes are exposed and already directly influenced. Hence, both "concentrations" and "climate" are resilient spheres that have a buffer effect before any abrupt danger caused by CDR intervention could reach the final stakes of humans. Considering that the CDR geoengineering measure is taken at time t_0, the intended cooling effect should take place at $t_0 + t_2$. Unintended side effects or even catastrophes caused by complexity and errors could arrive at $t_0 + t_2 + T'$. It takes considerably longer time, T, before a catastrophe reaches human society due to the buffer spheres in the feedback system.

The rationale here argues that from the "proximity of stake to catastrophe" perspective, by analyzing the feedback system, CDR is "less proximate" than SRM to human stakes. Comparing the distance of a possible catastrophe in SRM ($t_0 + t_1 + t'$) and CDR ($t_0 + t_2 + T'$), we argue that T' is generally longer than t' considering that the buffer effects in the feedback system. This results in less "*proximity of* stake *to catastrophe*". The buffer effect of "concentration" change and "climate" change would give us "some time" to take other urgent actions in case CDR leads us to the wrong direction. It's worth clarifying here that the "proximity of stake to catastrophe" philosophy does not aim to exclude the possibility of a catastrophe from CDR failures, nor does it intend to compare the detrimental effects of CDR and SRM malfunctions. One might give an example of CDR failure causing relatively quick detrimental effects: the failure of large-scale carbon storage. CCS, as a CDR approach, requires some place for storage of the scrubbed carbon dioxide. It has been proposed that the CO_2 be stored underground in cave systems, potentially using the geological space created by fossil fuel extraction. Were such storage sites to fail, there could be a rapid (on the timescale of days to months) change in the atmospheric CO_2 concentration and eventually a big influence on climatic conditions. However, CCS is, in general, a relatively decentralized approach. Therefore, to what extent the defection of a particular decentralized storage could influence the global CO_2 concentration and thereafter climate is debatable. Even if a large-scale carbon storage exists on earth, the failure of such a storage means a significant "emission" of CO_2 (upstream of the feedback system in Figure 2). The impact of such abrupt "emission" still has to go through "sinks" and "concentrations" step-spheres (therefore buffer effects) before the impact is evidenced in the "climate". Moreover, such changes are not linear processes. The higher CO_2 "concentration" will also trigger enhanced CO_2 uptake due to higher biomass productivity in elevated atmospheric CO_2 concentrations. Thus nature's buffer effects offset the detrimental impact and allow more time for man to look for other remedy solutions, such as using SRM or recapturing the leaked CO_2. One fact is that time is needed for such detrimental change in "emissions" to penetrate through the "sinks" and "concentrations" step-spheres and then "climate" to finally reach the stakes. Nevertheless, unlike the failure of CDR, malfunction of SRM (e.g., halting of the aerosol injection or defection of space mirror) will directly change the temperature in the "climate" where the stakes are exposed to. There is no or rare "buffer effects" for SRM failures in the couple climate-human systems.

It's not the purpose of this article ("proximity of stake to catastrophe") to give mathematical quantifications or prediction scenarios on how soon the impacts from each SRM or CDR failure will reach the final stake. The time for such impact diffusion largely depends on the nature and scale of the impact itself as well as the condition of the affected system. Especially in the complex adaptive climate-human systems, the t factor could be influenced by many other factors. Therefore, this article tries to interpret from a rather philosophical reasoning that qualitatively recognizes such buffer effects and the corresponding buffering time in such a feedback system. The "proximity" of the stake exposed to a possible catastrophe by either SRM or CDR intervention is therefore conceptualized by looking at whether buffer effects are available. While many "buffer effects" could be identified for CDR interventions on "emissions," "sinks," and "concentrations," limited natural "buffer effects" are available in such climate-human feedback systems once SRM geoengineering interventions fail. Taking such "buffer effects" and vulnerability of the stakes into account, this article gives a general philosophical interpretation for $t' < T'$ and aims to suggest such "proximity of stake to catastrophe" to be included as one principle, together with other principles, in the geoengineering decision-making process. In this sense, we conclude that SRM could be prepared as *Plan B* to rescue the adverse impact of CDR intervention if CDR fails to function properly.

The "proximity of stake to catastrophe" perspective gives a "timescale of risk" interpretation on the disadvantages of SRM or CDR, therefore suggesting that CDR is superior over SRM as the catastrophe is "less proximate" to the stake due to more buffers in between. While such philosophy paid precautionary attentions to the negative effects (catastrophe) of the climate-human systems, one might doubt the "proximity of stake to catastrophe" principle with an argument of the t factor on beneficial effects. Because of the same buffers and time cost through buffers, CDR interventions might be slower to achieve beneficial effects than SRM interventions. At first glance, such argument seems to undermine the "proximity of stake to catastrophe" philosophy. However, a closer look at such a trade-off reveals that this t on beneficial effects are less prioritized in geoengineering decision making due to the well-known "core precautionary principle" [16] and the more-or-less equivalent "anticatastrophe principle" developed and defended by Sunstein [38]. To some extent, the "core precautionary principle" is accepted and used as a sound decision principle for climate policy on climate mitigation or adaptation [39,40]. The precautionary principle, in general terms, aids our climate decision making to avoid the worst harm (catastrophe), particularly under uncertainties. In a choice between SRM and CDR, the "proximity of stake to catastrophe" should be more important than proximity of stake to beneficial effects, which is in line with the core precautionary principle. It is worth clarifying that we are not supporting the so-called "ultraconservative precautionary principle" which fundamentally neglects the beneficial effects. By prioritizing "proximity of stake to catastrophe," we position our framing closer to the core precautionary principle in terms of preventing harms when both harms and benefits are under uncertainties. The precautionary principle respects the maximin rule, a general principle for decision making under uncertainty [41]. To put it briefly, "*the one with the highest minimal possible payoff is rationally to be preferred from a set of alternative choices*". This maximin rule could help us gain clearer insight with a set of alternative choices in CDR and SRM. The CDR (slower benefit effects but less proximity of catastrophe) is therefore preferred to SRM (faster benefit effects but with higher proximity of catastrophe) when we simply compare the minimal possible payoff of each option. Therefore, in line with the precautionary principle and the maximin rule, we should adopt the anti-catastrophe perspective (as Sunstein defended) to incorporate the "proximity of stake to catastrophe" principle into decision making.

2.2. Can We Afford It?

While the previous session demonstrates CDR is generally superior over SRM from both the "essence of remedy" perspective and the "feedback loop system" perspective, this section might lead us toward an opposite conclusion when it comes to affordability. In general, albedo modification has a lower cost than emission abatement [42]. The Panel of Policy Implications of Greenhouse Warming calculates that injecting SO_2 aerosol into the stratosphere costs only pennies per tons of CO_2 mitigated [8]. This reveals the concept of cost of mitigation (COM) as the economic metric for geoengineering: dollars per ton of carbon emissions mitigated ($/tc). According to Keith, injection of CO_2 into the ocean ($50–150/tc), injection of CO_2 underground ($50–150/tc), and intensive forestry to capture carbon ($10–100/tc) have the highest COM, while the stratospheric SO_2 to increase albedo by direct optical scattering has the lowest COM (<<$1/tc). COM is thus used as a clear parameter to compare the cost between geoengineering and conventional abatement as well as between different geoengineering approaches [11]. There are two specific characters in terms of the cost of geoengineering and abatement. First, the cost of the albedo mitigation approach is not determined by the scale or the increasing pace of current anthropogenic emissions. One could target an albedo mitigation efficacy several times higher than anthropogenic forcing of climate change to achieve cooling the earth [11]. Second, albedo mitigation costs so little that this approach might be the most appealing to countries that seek environmental gain in a cheap way. These countries thus would deploy albedo geoengineering whenever they find it necessary. A single country could use geoengineering, especially albedo modification, to offset the impact from emissions, but this will also lead to problem shifting and moral hazard [18,43]. The availability of a faster SRM solution would possibly undermine the effort on CO_2 mitigation or increase the likelihood of mitigation failure. The root cause of global warming effect within the country has not been eradicated;

the warming effect has only been suppressed and delayed to sometime in the future when geoengineering doesn't work anymore for this in a small scale. Or these unilateral actions simply shift the problem to another country. Nevertheless, CO_2 mitigation calls for an unprecedented international collective effort that requires not only a huge budget for the mitigation technology and processes themselves but also investing a cooperative monitoring system, although this may also create jobs and have a beneficial influence on society.

With a global GDP of roughly $9 trillion, sunlight scattering is estimated as only costing $1 billion per year to offset global warming by 2100. Albedo geoengineering thus is widely regarded as costless. However, while injecting SO_2 aerosol into the stratosphere costs only pennies per tons of CO_2 mitigated, carbon dioxide capture and storage options would enable significant reductions in emissions from coal-fired generation, but the cost would be between $100–150/tc depending on the technology used [44]. Zenz *et al.* even claimed that the industrial air capture (IAC) scheme costs on the order of $1000 per ton CO_2 extracted from the atmosphere, and they described this as akin to a financial tsunami [45]. Especially for industrial emission CO_2 capture, the gigantic volume of gas that needs to go through the scrubber will require enormous amount of new infrastructures all over the world. The infrastructure system change will cause a significant increase in cost. The difference is huge so that we face a dilemma of choosing moderate good schemes involving CO_2 capture, which have higher certainty but also higher cost, or the affordable solar radiation management, which is highly uncertain.

2.3. Can Cost-Benefit be the Only Criterion?

As discussed above, aerosol geoengineering is commonly regarded as costless in proportion to the benefit it will achieve when compared to other approaches. Critics claim that CO_2 mitigation geoengineering is too expensive and that we would be better off using the budget to subsidize or invest in renewable energy systems instead of long-wave geoengineering. However, there are still scholars doubting cost claims of aerosol geoengineering, such as Goes *et al.* They pointed out that once the aerosol runs out of loading, abrupt adverse climate change effects will appear together with a monetary crisis [46]. While injecting aerosol into the stratosphere is relatively cheap, humans may build up future "costs" if the quick aid of aerosol geoengineering causes "moral hazard" and postpones our agenda of decarbonizing our economy. If cost-benefit is the only criterion, economists will argue for choosing the most economical solutions to tackle climate change. As aerosol geoengineering is in general more economically viable with its lower cost, it would be continuously preferred against putting effort into reducing CO_2 emission. In such a case, geoengineering causes a "rebound effect" of undiminished addiction to fossil fuels.

Regardless of whether some sort of geoengineering could be deployed at a marginal cost, the remaining question here is whether cost-effectiveness is the only criterion that guides our environmental decision making. Some other ethical issues also need our careful reflections—for instance, social equity, environmental ethics, hostile utilization risk, and moral authority. One wicked debate on geoengineering and CO_2 mitigation is that many geoengineering techniques intend to add something new into the environment on a planetary scale, while CO_2 mitigation aims at taking some "waste" out of the environment. Are we allowed to add new things into the planetary environment on such a scale? Some may argue that we have already tortured our environment so much, shall we have empathy and humanity to let nature recover by its own "Gaia effect"? Will the continuous anthropogenic modification at a planetary scale make the earth system even more fragile? The climate system is a complex adaptive system, and the intervention of geoengineering will probably add even more complexity to the system. As Ashby's Law of Variety reveals, "*The larger the variety of actions available to a control system, the larger the variety of perturbations it is able to compensate*", but how much complexity and variety should we add to our climate system? Even if we are tolerant with adding something new into the environment by geoengineering the climate, the new things added will stay in the climate for a long time. How do we know if our future generations have the same attitude or tolerance as us regarding interventions on natural systems?

2.4. Conflicting Interests and Values

This section elaborates on the "wickedness" from the dilemma of fairness and conflicting values, held by various stakeholders and even from different domains. The impact of a specific geoengineering approach on a planetary scale could be estimated by various climate models used by different scholars, which sometimes generate different results. There will always be different opinions toward global climate by different regimes. Robock's model suggests that sub-Saharan Africa would be even hotter and drier after global deployment of SRM, and the impact is much severer than global warming itself [27]. While SRM might cause this side effect in sub-Saharan Africa, it might also bring environmental gains as well, such as blocking the harmful UV radiation through the engineered particles. Is the UV-free area enjoying the environmental benefits at the cost of losers from sub-Saharan Africa? While there is UV blocking, there will also be ozone depletion. It has yet to be determined again which of these effects wins out on local and global levels. Russia, Canada, and the Nordic countries might already benefit from global warming and be in favor of this trend continuing [47]. However, in some parts of India, solar radiation is among the strongest levels in the world, and thus India might want a cooler degree. If India deploys stratospheric SO_2 aerosol injection, not only will the cooling effect worsen off Russia's environmental gain from global warming, but also, the aerosol particles injected into the atmosphere would be transported toward the pole and could likely cause acid rain in Russia. Should India then compensate the countries in the north for the environmental impacts? Will the north countries be the winners in both cases, either benefiting from global warming for agriculture production or from the compensation by the less developed India?

Geoengineering is thus commonly criticized because of its side effects. This is partly because it's usually intended to operate on a planetary scale and thus intervene in various earth cycles in global ecosystems. Stratosphere aerosol might cause a whitening of the sky and ozone depletion [31]. Ocean fertilization could cause side effect, such as decrease of dissolved oxygen and increase of methane from the ocean [48,49].

However, all these original global environmental problems (like global warming itself, ozone depletion, *etc.*) and those side effects caused by various geoengineering approaches (such as global sky whitening, global ocean dissolved oxygen decreasing, global acid deposition, *etc.*) are, at large, planetary-scale effects for which we simply don't have any weighting mechanism to evaluate or assess. Even if we have a weighting mechanism, scientists from different countries might be either in voluntary or forced by domestic political pressure to rank the importance of these effects in a different way to favor the stakes of their own regimes. This implies that scientists are able to objectively rank the effects of geoengineering, when in fact the ranking of these effects must also contain a subjective element. Different people might have different preferences. Scientific attempts to assess the effectiveness of geoengineering include "a risk-based framework" [50] or other "multicriteria" judgments [51]. There is hardly any global agency that can do a comprehensive environmental impact assessment for geoengineering. The conflicts across different institutional domains, different political interests, and different environmental aspects altogether constitute the wickedness and complexity of geoengineering. Geoengineering is thus far from achieving global agreement for a shared agenda in the international community.

2.5. Lack of Central Geoengineering Governance Authority

Just as the previous section illustrates, geoengineering deployed at various scales could result in opposite impacts on different parts of the world. The governance of geoengineering is far from indisputable. Ricke *et al.* (2013) outlined the different goals of geoengineering and the potential for international conflict [52]. The Solar Radiation Management Governance Initiative (SRMGI) (2011) has indicated a need for adequate resolution of uncertainties concerning the feasibility, advantages, and disadvantages of future geoengineering technologies and governance mechanisms [53]. The SRMGI evidenced the "hands-off" approach and "more comprehensive governance framework" approach as alternatives for geoengineering governance research. Among others, Bodansky paid attention to the fundamental governance issues raised by geoengineering, including the possible functions, forms, objects, and agents of governance [54]. The Oxford Principles [55] is one of the most influential set of principles on geoengineering governance, like the previously known Jamieson Principles and Belmont Principles.

Unlike other climate change solutions (greenhouse emission abatement), geoengineering could be implemented by a certain country alone for its own good. Those who suffer from global warming might take geoengineering as an urgent tool to achieve stabilizing the temperature within its own geographical boundary, while those who benefit from global warming might use geoengineering to strengthen instead of scattering solar radiation. There is continuous dispute on how geoengineering should be managed so that different stakeholders could deal with the consequences in a fair manner. Who could determine when, where, or whether a geoengineering approach should be tested and deployed? Should it be one intergovernmental agency evaluating proposals of geoengineering as well as monitoring its implementation on a global scale? Besides, because most geoengineering approaches would make "winners" and "losers", whether global governance should introduce the compensation mechanism, either based on causal responsibility or comparative wealth, should be considered [56]. The early stage of identifying "who will win" and "who will lose" would help on the negotiations of different stakeholders to effectively manage geoengineering fairly. Bidisha proposed using Jasanoff's "technology of humility" framework to involve vulnerable parties at early stages [57]. He claimed that the upstream engagement of different stakeholders—like policy makers, citizens, scientists, and NGOs—to assess the distributive impact of geoengineering is of vital importance to take vulnerable people's stakes into account during policy making [19]. The lack of a central geoengineering governance authority and participatory policy making could only cause delay of proper global collective geoengineering implementations. At the same time, because each country might be waiting for other countries' first-step efforts, this could result in a hyperbolic discounting effect in each regime (although they recognize the overwhelming evidence of global warming, they just take policy measures that focus on the short term in their own regimes, especially related to political cycles, and disregard the severe consequences of global deterioration), and in the end, we might run out of time.

2.6. The Tuxedo Fallacy in Geoengineering Decision Making

In decision-supporting disciplines, it's recognized that there exists a tendency to proceed as if reasonably reliable probability estimates were available for all possible outcomes. This is termed as "tuxedo fallacy" [58]. As Hansson put it, "It consists in treating all decisions as if they took place under epistemic conditions analogous to gambling at the roulette table" [59]. Many existing criticisms of geoengineering have focused on the side effects of various options in both SRM and CDR by estimating the possible end-point impacts of each option. Nevertheless, technologies of SRM and CDR are different in terms of action modes, timescales, and efficacy of deployment. Facing these diverse and radically new technologies, how should rational decision making be conducted to choose the most efficient and effective option in different contexts? Engineering decision making requires taking the probability of technological failure into account. There are many cases in which humans obtained statistically sufficient experience on particular technologies. The probability of technological failures could be determined in such cases when the technologies are well established and one can learn from experiences, such as serious accidents (e.g., aviation accidents). For geoengineering technologies, we might be able to learn about the probability of failure from small-scale experiments. For example, it might be possible to assess the technology without actually doing aerosol injection on a planetary scale. However, learning about the climate impacts is not possible without full-scale deployment. It is very difficult and risky to test geoengineering on full-scale deployment [60]. Besides, geoengineering options manipulate our climate environment on a planetary scale so that any accident could cause severe and irreversible impacts on a large scale. Humans are vulnerable to the possible detrimental failure from doing experiments with the planetary environment through some geoengineering options, not to mention whether the technology is relatively well mastered (such as engineered carbon capture) or radically innovative and untested (such as placing shields or deflectors in space to reduce solar energy reaching earth). The interaction of radically new and untested technology with a complex climate system determines the options in geoengineering not at risk but under uncertainty. It's difficult for scientists to judge the risk (probability) of accidents without statistic record, and it's dangerous to give subjective probability for decision making in choosing geoengineering options. Adopting some radically new geoengineering technologies is like entering a jungle previously untrodden by humans. The situation we face regarding diverse geoengineering options is more jungle-like than casino-like—as Hansson put it, the "tuxedo fallacy" [59]. Those who make decisions in geoengineering options must take note of this "tuxedo fallacy."

3. Conclusions

This article discusses social and ecological aspects of large-scale technological interventions into the climate system, and further summarized the wickedness and complexity of geoengineering from a system perspective by identifying the interventions of the two major types of geoengineering, SRM and CDR, at the various phases of the earth cycle feedback system. Through a “proximity of catastrophe to stake” argument, CDR prevails over SRM because it leaves more “buffer time” for humans to take urgent remedy actions if a severe impact in a system occurs due to improper planetary intervention. This systemic perspective is also in line with argumentations on the different fundamental natures of these two types of approaches. However, the comparative strength of CDR over SRM failed to bring it ahead on policy agendas due to the huge cost of most CDR approaches compared to relatively more economic SRM measures. Under current political and sociotechnical landscapes, whether or not cost-efficiency could be the only criterion in terms of climate policy making has been widely discussed. Together with other ethical dilemmas and other conflicting interests, the choice, management, and assessment of geoengineering have become a wicked issue. This article thus deals with “wickedness and complexity” of decision making in geoengineering, starting from the murky definition to later highlighting that there is no accepted weighting mechanism of geoengineering side effects and impacts but various conflicting values and stakes crossing institutional domains and political boundaries instead. In order to minimize the conflicts from different stakeholders, this article suggests a central geoengineering governance authority, which devotes itself to reducing the wickedness and complexity of geoengineering. Bernstein’s four features of “super wickedness”—namely “Time is running out”, “No central authority”, “Those seeking to end the problem are also causing it”, and “Hyperbolic discounting”—have been embedded in the philosophical argumentation and elaborations in the article. By a systematic overview of the wickedness and complexity of geoengineering from the human-climate relationship, economic viability, social impacts, ethics and governance aspects, this article reveals that it’s a wicked problem and complex issue for decision making in geoengineering under current socio-political-technical landscapes.

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Author Contributions

Yanzhu Zhang contributed to the original idea of the study and drafted the manuscript. Alfred Posch helped with a critical revision of the paper and its strategic direction during the whole publication process. The final manuscript was approved by both authors.

Conflicts of Interest

The authors declare no conflict of interest.

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