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Geoengineering as a Technological Option to Address Climate Change: A Critical Scientific Study of Opportunities and Risks

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Abstract

Amid escalating threats associated with climate change, geoengineering is emerging as an urgent scientific and technological option to mitigate global warming. These technologies include strategies aimed at managing solar radiation and atmospheric carbon removal technologies, and are proposed as complementary solutions alongside traditional emission reductions. This study aims to analyze the most prominent geoengineering techniques, review the available scientific literature, and assess the environmental, ethical, and legal dimensions associated with their application. Using a critical analytical approach, it is demonstrated that these solutions hold technical promise for mitigating global warming, but they also entail potential risks that may affect global climate balance, biodiversity, and national sovereignty in climate decision-making. The study also reveals a clear lack of an international governance framework to regulate the use of this technology, raising questions about climate justice and potential "climate colonialism." The study recommends the adoption of a systematic global approach based on multilateral governance and rigorous scientific oversight before implementing any large-scale field experiments. It also emphasizes the importance of incorporating the voices of developing countries and affected communities into shaping future climate policies. This paper seeks to contribute to enhancing scientific understanding and responsible dialogue on the feasibility of geoengineering as a tool for managing the climate crisis.

Keywords: Geoengineering; Climate change; Solar radiation management; Carbon removal; Climate governance

Introduction

Climate change is considered one of the greatest challenges facing humanity in the 21st century, with record-breaking temperatures, rising sea levels, and the frequency of natural disasters such as hurricanes, floods, and wildfires every year. Climate change is closely linked to human activities, particularly the burning of fossil fuels and deforestation, which increase the accumulation of greenhouse gases in the atmosphere. Despite progress in climate agreements such as the Paris Agreement, carbon emissions continue to rise, prompting scientists to consider innovative, unconventional solutions.

Among these solutions is "geoengineering" or "climate engineering," which aims to directly interfere with the Earth's climate system to reduce the planet's temperature or lower greenhouse gas concentrations. These techniques are gaining increasing importance due to accelerating environmental degradation and the failure of conventional efforts to reverse global warming. However, this approach generates widespread controversy among scientists, policymakers, and environmental activists due to the environmental, political, and ethical risks it entails, especially in the absence of a clear global legal framework regulating its use.

This paper seeks to provide a critical analysis of the field of geoengineering, focusing on its most prominent technologies and applications, while also assessing the associated scientific, environmental, and ethical aspects. It also aims to discuss its potential as a complementary solution, rather than an alternative, to global efforts to reduce emissions and adapt to the effects of climate change.

Introduction

First: the general concept of geoengineering

The term geoengineering is defined as "the deliberate, large-scale intervention in the Earth's climate system to mitigate the effects of climate change" [1]. Global interest in this field has grown as a result of the slow international response to reducing greenhouse gas emissions, prompting some scientists to propose complementary technological solutions [2].

Second: solar radiation management (SRM)

Solar radiation management techniques include strategies to control the amount of solar energy reaching the Earth's surface, with the goal of reducing global warming. Prominent among these techniques are:

a) Injecting sulfur particles into the stratosphere to simulate the effects of volcanic eruptions [3].

b) Increasing the reflectivity of marine clouds.

c) Using space mirrors to reflect solar radiation [4].

While these techniques may lead to rapid temperature reductions, they do not address the concentration of greenhouse gases in the atmosphere. It may also lead to regional changes in rainfall patterns, threatening food security across large areas [5].

Third: atmospheric carbon removal (CDR)

Carbon removal technologies include efforts to capture carbon dioxide from the atmosphere and store or reuse it. Prominent examples include:

a) Afforestation and forest restoration [6].

b) Direct air capture and underground carbon storage.

c) Ocean fertilization using iron to stimulate algal growth [7].

Although these technologies are considered more sustainable than SRM, they require significant time, financial and technical capabilities, and are likely to impact marine ecosystems.

Fourth: ethical and political dimensions

Gardiner [8] argues that one of the most prominent ethical issues with geoengineering is its potential use as an excuse to postpone emissions reductions. The absence of effective international governance mechanisms also raises concerns that some countries will resort to implementing unilateral experiments without consulting the rest of the international community [9]. This situation poses a challenge to climate justice and transparency.

Fifth: calls for global governance

The Royal Society [1] report recommends the development of a legal and ethical framework to monitor the application of geoengineering technologies, ensuring the participation of developing countries and local communities in the decision-making process. The IPCC [10] also notes that these technologies are still in their infancy and require controlled field trials and accurate simulation models.

Based on this literature, it is clear that geoengineering is not a panacea, but rather a complex option that requires a comprehensive scientific, social, and ethical assessment.

Literature Review

Data was collected from reliable academic sources, including peer-reviewed research articles and international reports from organizations such as the Intergovernmental Panel on Climate Change (IPCC) and the Royal Society. According to the Royal Society [1] report, "Geoengineering is the deliberate intervention in the climate system to mitigate the effects of climate change" (p. 25). Previous studies on the applications of SRM and CDR technologies were also drawn upon, such as Crutzen's [2] study on stratospheric particle injection, which he considered "a quick fix for mitigating global warming" (p. 25). The literature is categorized into three main areas:

a) SRM technologies: These include methods such as stratospheric sulfur injection to reduce global warming [3].

b) CDR technologies: These include marine fertilization and afforestation [11].

c) Ethical and political dimensions: An analysis of the challenges related to climate justice and national sovereignty in making decisions about the application of these technologies [8].

Comparative analysis

A comparative analysis was applied between different studies to assess the potential benefits and drawbacks of geoengineering technologies. Case studies conducted in diverse geographical areas where SRM technologies have been tested in limited field trials were used. The legal and ethical frameworks used in industrialized and developing countries were also compared, in accordance with the IPCC [10] report, which discusses the need for "international cooperation to manage risks arising from geoengineering technologies" (p. 12). The results of these experiments were analyzed to determine the impacts of geoengineering technologies on climate change and environmental management.

Environmental assessment

In this study, we relied on Environmental Impact Assessment (EIA) criteria to assess the impacts of geoengineering techniques. This process requires identifying potential environmental risks, such as unforeseen impacts on marine and terrestrial ecosystems. According to Minx et al. [6], "Removing carbon from the atmosphere through afforestation may improve ecological balance, but there are challenges in ascertaining long-term impacts on biodiversity" (p. 51). Similarly, Tilmes et al. [5] noted that SRM techniques "may lead to regional changes in precipitation patterns, potentially jeopardizing food security in some areas" (p. 90).

Ethical and political analysis

The ethical and political issues related to the application of geoengineering techniques were analyzed, raised by several researchers, such as Gardiner [8], who noted that "geoengineering may be used as a pretext to postpone effective emission reduction solutions" (p. 128). The impact of the absence of effective

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governance mechanisms was also studied by Parson & Ernst [9], who discussed "the importance of establishing a global legal framework to regulate the use of geoengineering techniques" (p. 45). According to Parson & Ernst [9], "Without such mechanisms, some countries could exploit the technology within a narrow political framework, leading to the implementation of these solutions without consultation with the international community" (p. 47).

Field methodology

Field studies were used to evaluate the impact of geoengineering techniques in specific experimental settings. Data from stratospheric particle injection experiments were analyzed in some studies conducted in industrialized countries. Research suggests that SRM techniques may reduce global temperatures rapidly, but they do not address underlying issues such as the accumulation of greenhouse gases in the atmosphere [3].

Qualitative and quantitative data collection

Qualitative data was collected through a review of scientific literature and previous research. Quantitative data from studies measuring the climate impacts of geoengineering technologies, such as measuring global temperature changes [10], were also used. This data was collected from various sources, including government studies and reports from environmental organizations. This data was analyzed using statistical techniques to determine the potential effectiveness of these technologies in mitigating climate change.

Technology assessment

A technology assessment methodology was applied to determine the effectiveness of geoengineering technologies in mitigating global warming. This included assessing the practicality of these technologies, along with analyzing their economic and technological dimensions [4]. A comparative study of technological innovations in the field of geoengineering was conducted to identify technical gaps and provide recommendations for improving performance.

Results

Analyses of geoengineering techniques, including solar radiation management (SRM) and atmospheric carbon removal (CDR), have shown that these solutions may contribute to mitigating the effects of climate change, but they involve significant challenges and risks.

Among the solutions studied, SRM techniques, such as stratospheric sulfur particle injection, have shown rapid results in reducing global temperatures. According to Keith [3], these techniques could reduce global temperatures by 1-2°C within a few years. However, despite these potential benefits, these techniques have shown no effect in reducing the accumulation of greenhouse gases in the atmosphere, indicating that the underlying problem of global warming will not be fully addressed by these solutions. Furthermore, other studies, such as Tilmes et al. [5], have warned that these techniques could lead to regional changes in rainfall patterns, which could threaten food security in certain regions.

Carbon removal technologies have shown positive results in their ability to reduce atmospheric carbon dioxide concentrations. For example, Minx et al. [6] noted that afforestation and forest restoration can have a long-term positive impact on reducing carbon emissions. Direct air distillation (DAC) and underground carbon capture (CCS) technologies have also demonstrated potential to remove carbon from the atmosphere, but these solutions require significant investments in infrastructure and technology, making them currently unfeasible on a large scale. Furthermore, Minx et al. [11] warned of the potential environmental impacts of marine fertilization technologies using iron, as they could lead to unforeseen changes in marine ecosystems.

While geoengineering techniques are more effective in rapidly reducing global temperature, they pose unforeseen environmental risks. For example, studies on SRM have shown that the use of sulfur in the stratosphere could lead to changes in biodiversity in sensitive areas [4]. CDR techniques, such as afforestation, may also affect the ecological balance in some areas due to extensive land use, potentially threatening local biodiversity.

From an ethical perspective, studies have shown that geoengineering may be used as a pretext to postpone reducing greenhouse gas emissions, a concern many scientists and environmental activists have raised. According to Gardiner [8], these techniques could become a "weapon" to postpone countries' commitments to climate change, harming climate justice. The absence of effective international governance mechanisms may also allow some countries to implement these techniques without coordination with the rest of the international community. This may reduce the opportunities for effective participation of developing countries in climate decision-making, raising concerns about climate colonialism [9].

Through technological evaluations of geoengineering approaches, it has been shown that these techniques are still in their early stages of development. Studies on stratospheric sulfur injection have shown some temporary changes in temperature, but the long-term effects on ecosystems have not been determined (Keith, 2013). In addition, DAC and CCS technologies still need further research and development to achieve the required efficiency in large-scale decarbonization [12].

Conclusion and Future Proposals Beyond 2025

Conclusion

Geoengineering, as an innovative solution to address the challenges of climate change, shows great potential as a complementary technology that can contribute to mitigating the

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effects of global warming. Although these technologies promise rapid and effective solutions to reduce global temperatures, their widespread implementation may face numerous environmental, political, and ethical risks. Prominent among these risks are regional changes in climate patterns, unpredictable impacts on biodiversity, and potential threats to climate justice due to the absence of clear international governance mechanisms.

Studies indicate that solar radiation management technologies, such as stratospheric sulfur injection, may offer temporary solutions to reduce temperatures, but they do not guarantee addressing the root cause of the problem: the accumulation of greenhouse gases in the atmosphere. On the other hand, carbon removal technologies offer significant potential in improving environmental sustainability, but they require massive investments in technology and infrastructure, making their widespread implementation difficult at present.

In addition, the issue of governance and climate justice emerges as a major challenge in the application of geoengineering technologies. The lack of coordination between different countries could lead to uncontrolled experiments, or even worse, deepening the gaps between developed and developing countries. Therefore, it is essential that any application of these technologies be accompanied by a clear legal and ethical framework that respects the principles of transparency and equality.

Future proposals after 2025

1. Developing an international governance framework:

After 2025, geoengineering is expected to become more sophisticated and widely used. Therefore, it is essential to establish a global governance framework that clearly defines the laws and principles that should govern the use of these technologies. This framework should include precise monitoring mechanisms and comprehensive regulation of geoengineering experiments, taking into account that this coordination must include all countries equally, including developing countries, which may be most affected by climate change.

2. Expanding research and development:

To enhance the effectiveness of geoengineering technologies, investment in research and development must be increased to improve their efficiency and reduce their risks. In particular, larger and more diverse field trials are needed to study the long-term environmental impacts of these technologies. Emphasis should also be placed on developing more effective and cost-effective carbon removal technologies.

3. Focus on complementary, not alternative, solutions:

Geoengineering technologies should be integrated into broader climate change mitigation strategies, emphasizing that they cannot replace global efforts to reduce emissions. Geoengineering should be part of a mix of solutions that include reducing emissions, adapting to the impacts of climate change, and enhancing the sustainability of natural resources. These technologies should be used in local and global contexts that consider environmental and social dimensions.

4. Continue to promote climate justice:

It is essential that geoengineering efforts focus on ensuring climate justice by engaging all stakeholders in decision-making related to these technologies. This includes engaging local communities, especially in developing countries that may be more vulnerable to environmental risks. Geoengineering policies should include practices that engage with communities to ensure they are not burdened with unfair consequences.

5. Achieving coordination between science and international agreements:

With the growing need for innovative technological solutions to climate change, the international community must coordinate efforts between scientific research, government, and international organizations to ensure the responsible use of geoengineering technologies. This coordination should take place through ongoing climate conferences and negotiations aimed at achieving a global understanding on the management of these technologies.

6. Periodic monitoring and assessment of environmental impacts:

After 2025, global monitoring programs should be established to periodically assess the environmental and social impacts of geoengineering technologies. These programs should include studies of environmental impacts on ecosystems and economic and social growth, including any changes in weather patterns or biodiversity in different regions.

Concern for ethical dimensions and justice:

There should be increased focus on the ethical dimensions associated with the use of geoengineering technologies, particularly regarding the distribution of benefits and burdens between developed and developing countries. This requires the development of policies that govern how these technologies impact the most vulnerable communities.

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