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Human Rights and Precautionary Principle: Limits to Geoengineering, SRM, and IPCC Scenarios

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Abstract: Most scenarios on instruments limiting global warming in line with the 1.5 °C temperature limit of the Paris Agreement rely on overshooting the emissions threshold, thus requiring the application of negative emission technologies later on. Subsequently, the debate on carbon dioxide removal (CDR) and solar radiation management (SRM) (frequently subsumed under "geoengineering") has been reinforced. Yet, it does not determine normatively whether those are legally valid approaches to climate protection. After taking a closer look at the scope of climate scenarios and SRM methods compiling current research and opinions on SRM, this paper analyses the feasibility of geoengineering and of SRM in particular under international law. It will be shown that from the perspective of human rights, the Paris Agreement, and precautionary principle the phasing-out of fossil fuels and the reduction in consumption of livestock products as well as nature-based approaches such as sustainable—and thus climate and biodiversity-smart—forest, peatland, and agricultural management strongly prevail before geoengineering and atmospheric SRM measures in particular. However, as all of the atmospheric SRM methods are in their development phase, governance options to effectively frame further exploration of SRM technologies are proposed, maintaining that respective technologies thus far are not a viable means of climate protection.

Keywords: geoengineering; solar radiation management; IPCC; human rights; precautionary principle; Paris Agreement; scenarios; climate governance

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1. Introduction and Scope of the Paper

Human-induced climate change above certain thresholds will have irreversible and largely negative effects on human livelihoods, biodiversity, and ecosystems as a whole [1]. In the Paris Agreement (PA), states have legally committed to limit global warming to well below 2 °C and to pursue efforts to limit it to 1.5 °C above pre-industrial levels (Art. 2 para. 1 PA). The legally binding nature of the overall objective is neither changed by the fact that the reduction measures and therefore the implementation of the PA is based on nationally determined contributions (NDC), nor the missing mandatory implications of adaptation, finance, and loss and damage (see Chapter 4.1 and [2]). The 1.5 °C target requires us to neutralize the remaining greenhouse gas (GHG) emissions, meaning "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Art. 4 para. 1 PA). To reach net zero emissions, firstly, GHG emissions have to be minimized effectively as much as possible. Furthermore, it will be necessary to compensate for residue GHG emissions that cannot be mitigated even with a cap zero for fossil fuels and drastically reduced livestock farming (see in detail [2,3]). However, there is a considerable gap between the real actions taken by states and the requirements of the PA, also referred to as "emissions gap" [4]. There are three general approaches to reducing GHG emissions, albeit the boundaries between the individual approaches are partly fluent, and the terminology varies more or less wildly, as we will see in the following. From the epistemological point of view, definitions as such are never right or wrong [2]. They serve to clarify the intent of an analysis. The distinction we prefer consists of following three elements:

(1) Reduction in GHG emissions, which is mainly achieved by phasing out fossil fuels and globally minimizing livestock farming [5–7].
(2) Compensation of residual emissions by enhancing natural sink capacities in the land-use sector, specifically through forest management, rewetting of wetlands, and agricultural management [8–11].
(3) Compensation of residual emissions by means of technical large-scale interventions to enhance sinks (e.g., direct air CO_2 capture and removal or ocean management), or to directly alter the Earth's radiative energy (e.g., deliberate changes in the atmosphere or use of albedo effects) [12,13].

In the majority of states, there are no sufficiently ambitious post-fossil pathways, etc., and there is a lack the political will to implement respective measures. Therefore, large-scale, technologically driven interventions, subsumable under the term climate-related geoengineering (in the following geoengineering), seem to bear the promise of a smart way out of the crisis without changing technology-based paradigms. However, the classification of individual measures under this generic term is variable so that it makes sense to specify precisely which concrete measure is considered, as we will see in the following.

With regard to the various compensation options, the Intergovernmental Panel on Climate Change (IPCC) follows a different distinction than the one we offered above. The IPCC states in its climate mitigation report of 2014 that geoengineering techniques cover a "broad set of methods and technologies" [1], p. 1262, which aim to "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change". It makes a distinction between carbon dioxide removals (CDR) and solar radiation management (SRM) measures [14] (p. 89). CDR (in the case of storing GHG other than CO_2 called greenhouse gas removal) aims at removing GHG emissions directly from the atmosphere, either by increasing natural sink capacities, e.g., via biomass creation or non-natural sink capacities or via chemical engineering [15,16] (p. 8). The IPCC defines CDR as "anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities" [17] (p. 544). SRM, in contrast, includes measures that aim at directly modifying the Earth's radiative energy budget to generate a cooling effect [1,12,18]. According to the IPCC, SRM "refers to the intentional modification of the earth's shortwave radiative budget with the aim of reducing warming" and "does not fall within the definitions of mitigation and adaptation" [17] (p. 558). Table 1 compiles the different CDR and SRM measures, which the IPCC subsumes as geoengineering. CDR covers both the enhancement of natural sink capacities in the land-use sector through improved agricultural practices (e.g., through enhanced soil carbon sequestration) or afforestation and reforestation and chemical or mechanical carbon storage through bioenergy with carbon capture and storage (BECCS), direct air carbon dioxide capture and storage (DACCS), or ocean alkalization and fertilization [17](p. 345). The IPCC already considered the enhancement of natural sink capacities in 1990 [19] (pp. 113,118) while carbon storage appeared later [20]. The term SRM covers ideas such as changing the surface albedo by whitening roofs, which are rather riskless and potentially high-risk atmospheric approaches aiming at changes in precipitation patterns and global circulation regimes [17] (p. 348).

Table 1. Geoengineering approaches according to the Intergovernmental Panel on Climate Change (IPCC), different to the narrower definition presented above (own table, based on [17] (pp. 342–351).

	Carbon Dioxide Removal (CDR)		Solar Radiation Management (SRM)
1	Bioenergy with carbon capture and storage (BECCS)	7	Stratospheric aerosol injection (SAI)
2	Direct air carbon dioxide capture and storage (DACCS)	8	Marine cloud brightening (MCB)
3	Enhanced weathering and ocean alkalization (EW)	9	Cirrus cloud thinning (CCT)
4	Afforestation and reforestation (AR)	10	Ground-based albedo modification (GBAM)
5	Soil carbon sequestration and biochar		

On the one hand, it is pretty obvious that a net-zero-emission target requires some compensation, since it is hardly possible to cut down emissions to zero in some sectors, especially in agriculture. On the other hand, each of the compensation options can be critically assessed regarding their risks and possible counteracting factors compromising their storage potential [21,22] (e.g., for the ambivalence of biomass production as one part of BECCS, see [23] or regarding large-scale afforestation see [24–29]). In this paper, we focus on a critical assessment of geoengineering in the narrower sense of the definition given above. From the perspective of the law, we will assess the risks of large-scale technological interventions to directly alter the Earth's radiative energy, with references to other measures where appropriate. Regarding the underlying natural scientific facts, we focus on one single example, because taking all the different approaches into account would go beyond the scope of one single article: atmospheric SRM approaches, in particular stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus cloud thinning (CCT). Recent climate scenarios used in the IPCC reports (see also [17]) contain ever-shrinking emission budgets, also giving rise to discussions about BECCS and afforestation/reforestation. Additionally, atmospheric SRM technologies are increasingly scientifically discussed in terms of the extent to which they might be viable options in combating climate change [12,30–37].

Evaluating geoengineering, and in particular SRM technologies (SAI, MCB, and CCT), contains normative questions [38–41]. In a liberal–democratic framework, the law provides the basis for answering normative questions. In this case, this specifically means human rights, the precautionary principle, and other principles of (international) law. Normative questions are not up to individual ethical discretion—which is sometimes forgotten when, e.g., the IPCC reports discuss "ethical" questions of climate change (for more details on ethics and law in general and with regard to climate change in particular see [2]). Natural sciences provide knowledge and propose (technological) solutions to decision-makers, which are implemented by means of policy instruments. Policy instruments can be measured against the normative goals and limits of the law [2]. This is why, in a first step, we will critically review the natural scientific debate regarding SAI, MCB, and CCT, as examples of large-scale technically based geoengineering options to combat climate change. Building on that, we will carry out our legal analysis. This includes a legal assessment regarding the relation of (1) phasing out fossil fuels and cutting emissions from the livestock sector, (2) enhancing natural sink capacities in forests, wetlands, and agricultural used soils, and (3) the application of the assessed atmospheric geoengineering technologies SAI, MCB, and CCT. In the last step, we also aim to contribute to the further research question how and to what extent potentially high-risk atmospheric SRM strategies, including potential field experiments, could be regulated.

2. Methodology

Regarding the methodology, we will conduct two steps. Firstly, we will critically outline the highly contentious debate on geoengineering in general and on atmospheric SRM in particular by reviewing the relevant literature. We will then take a closer look on the role of the IPCC, its climate scenarios, and the uncertainties of projections. This is helpful, since the scenarios are the vital basis of the ongoing debate on the different geoengineering options with a special focus on legal implications. The IPCC's Fifth Assessment Report (AR5) and the Special Report from 2018 (SR1.5)

[1,17] as well as supplementary literature on the uncertainties of climate models and their background assumptions function as the basis of the review. We will question the concealed normative character of IPCC scenarios and will distinguish between generated natural scientific knowledge and legal interpretation. With regard to the natural scientific findings of the selected SRM technologies, a brief literature review reflecting the ongoing debate is being carried out. Given the quite controversial state of the natural scientific debate on different SRM options, this critical review serves as a factual background for the legal analysis, which will subsequently be the major component of the paper.

Secondly, the basis for implementing geoengineering and atmospheric SRM approaches in particular is assessed in a legal analysis considering climate legislation under international environmental law and human rights. Methodologically, we will apply a legal interpretation of the respective legal norms. Because the application of the chosen SRM strategies has an international scope, the legal interpretation will also be of international environmental agreements, focusing on the PA next to the Convention on Biological Diversity (CBD) and other multilateral agreements. Legal norms are interpreted grammatically or textually (related to the wording of a norm), systematically (taking the relation of the respective norm to other norms into account), teleologically (referring to the purpose of a norm), and historically (see, e.g., Art. 31 of the Vienna Convention on Contract Law). This means according to their literal meaning, their relation to other legal norms, their purpose, and their historical background. Usually, grammatical and systematic interpretation is applied because the other two approaches are prone to several problems, such as vagueness and the lack of a clear methodology to determine the "purpose" of a norm [2]. In the Anglo-Saxon legal sphere, case law would also be used as a source of interpretation. Whether this is methodologically convincing or not is left open here, since there is a lack of court judgments on the topics of this paper.

3. Challenges in Terms of Natural Science—the IPCC, Overshoot Scenarios, and SRM

3.1. The IPCC, Climate Scenarios, and Modelling

At the beginning of the natural scientific analysis, some critical remarks on models of the IPCC are necessary. Today, models are usually the framework within which discourses on options such as geoengineering unfold. Art. 2 para. 1 PA has determined that the consequences of global warming of 1.5 °C—or, if impossible, at most "well below 2 °C"—are the limit of what is normatively acceptable in terms of adverse effects on ecosystems and livelihoods. This objective is measured against climate projections of the IPCC. The IPCC compiles data from a variety of climate research on the effects of GHG emissions on the atmosphere and the probable consequences climate change will have and regularly publishes reports summarizing the current state of climate science and providing projections.

The projections themselves do not have any normative indication, similar to natural scientific data that have per se no normative status (otherwise, a fallacy of "is" and "ought" would occur; see in detail [2], as well as on roots and frictions in the writings of Kant and Hume). Furthermore, any scenario is confronted with several unknowns and makes background assumptions that simplify every model. These variables show huge effects on the outcomes [6]. Budgets of the remaining emissions to stay within 1.5 °C global warming provide a (oftentimes very thorough) estimate of the development of the global climate under certain influences. The underlying model, however, is not a real calculation in the stricter sense [6], as they are based on a high number of assumptions. Furthermore, the climate system is a complex and highly volatile system in which a number of factors react to various changes [42]. Even though it follows the laws of physics, some degree of uncertainty is inherent to all predictions of the development of the climate system (this is in addition to the uncertainty we are always subjected to when concerned with the future). Geophysical uncertainty is rooted in the uncertainty about non-CO_2 responses and the transient climate response to cumulative carbon emissions (TCRE). In the scientific presentation, a range of emission budgets is given according to the probability with which it will reach a temperature target taking an average from the different scenarios evaluated.

Attempting to account for the future of human development adds another layer of uncertainty. This uncertainty includes both the perspectives of economic and population growth and the changes brought about by political action, which directly or indirectly have an impact on the climate [43–45].

In its Fifth Assessment Report, the IPCC estimates a remaining budget of 400 $GtCO_2$ (CO_2 only, not CO_2 equivalents) to avoid more than 1.5 °C warming with a 66% certainty from 2011 [1], p. 74, Table 2.2. In the Special Report on Global Warming of 1.5 °C of 2018, the IPCC raised the budget for a 66% chance of avoiding 1.5 °C to 420 $GtCO_2$—or 10 years of current emissions. Similarly, the budget for a 50% chance of exceeding 1.5 °C increased to 580 $GtCO_2$—14 years of current emissions [17]. This budget looks at CO_2 emissions only, estimating that "the level of non-CO_2 mitigation in the future could alter the remaining carbon budget by 250 $GtCO_2$ in either direction (medium confidence)." [14]. This difference has several causes: Firstly, there is a normative disagreement about the 1.5 °C target. While some seem to believe that it is sufficient to orient policies towards reaching it with a 50% certainty, there are strong arguments to assume that not even 66% certainty is sufficient (argued in detail in [6]). Secondly, regarding "pre-industrial level" as a benchmark against which to measure global warming, legal questions are when to set the date and which temperature level is assumed (estimated difference of +/−250 $GtCO_2$). Related to that, since datasets become scarcer and less exact the further one goes back, it is significant which observational temperature datasets are used (estimated difference of +/−300 $GtCO_2$). Thirdly, all models are still inadequate in terms of their complexity. Further uncertainties are added to all kinds of models by a lack of understanding (and the missing means to simulate) some feedback and physical processes associated with global warming. Furthermore, natural cycles such as the carbon cycle cannot yet be fully anticipated in terms of the developments and capacities of sinks and sources (this regards both terrestrial and the oceans) [46]. In addition, it is yet uncertain when and to what degree certain options are ready for deployment on a larger scale [47]. The scenarios do not yet fully account for the effects of non-CO_2 GHG, even though their impact on the climate is significant [48,49]. As has been shown elsewhere [6,50], all these uncertainties and the overseen legal aspects lead to the conclusion that budgets are rather overestimating the remaining emissions that can still be emitted without surpassing 1.5 °C global warming.

While these factors already account for a huge variability in the budget, most scenarios shown by the IPCC SR1.5 assume overshooting the temperature limit to around 1.8 °C and that, by generating negative emissions, the temperature can be lowered back to 1.5 °C by the end of the century. This expands the budget by 400 to 1600 $GtCO_2$ (the equivalent of 10 to 40 years of current emission levels) [51]. Therefore, methods of CDR play an exceedingly large role in climate protection. However, "(q)uantifying how the carbon cycle responds to negative emissions is an important knowledge gap for strong mitigation pathways" [17]. Concretely, it is still unknown whether returning to a lower temperature level is at all possible, considering the complexity of geophysics, and, if so, how. This would include maintaining ecosystems while emission concentrations first rise and then sink within a short time. Inertia of the carbon cycle and the mean temperature of the seas are hard to predict and not yet sufficiently understood. Probably, there are tipping points that will be reached once global warming approaches 1.7 to 1.9 °C, which will lead to irreversible effects triggering further consequences [17,52–54]. In addition, overshoot scenarios bear the strong possibility of triggering negative socioeconomic effects, comprising livelihoods and burdening future generations [55–57]. In addition, adapting to first increasing and then decreasing temperatures within a matter of decades puts a double-strain on biological diversity [58–60]. Furthermore, there may be biophysical restrictions [48,61,62], some of which will be discussed in the following. Most important for the purpose of this paper: whether certain CDR and SRM options made necessary by an overshoot are allowed or not is a legal question. Scenarios, apart from all the uncertainties, cannot answer these questions.

3.2. Assessment of Geoengineering Options—the Example of Atmospheric SRM Approaches

The Fourth Assessment Report of the IPCC discusses geoengineering, particularly stratospheric aerosol injection and ocean fertilization, concluding that they are "largely speculative and unproven, and with the risk of unknown side effects" [61]. The Fifth Assessment Report in 2014 for the first time mentions different SRM and CDR technologies together under the term geoengineering [1] and includes bioenergy with carbon dioxide capture and storage [29,48,63,64]) and afforestation as CDR strategies in climate scenarios [1]. As pointed out in Chapter 1, in SR1.5, the term geoengineering is not used often anymore, separately considering CDR options—including the anthropogenic enhancement of natural sinks—and atmospheric as well as ground-based SRM methods [17]. Within the climate models of the IPCC, BECCS, and AR are—so far—the only CDR methods included in pathways with overshoot scenarios. However, even regarding these scientifically less controversial approaches, the IPCC still states that "CDR deployed at scale is unproven, and reliance on such technology is a major risk in the ability to limit warming to 1.5 °C" [17] (p. 96). In any case, SRM options attract a lot of interest, since they bear the promise to stop or at least delay global warming faster than, e.g., AR or the restoration of degraded forest and wetland ecosystems, with projected effects in the span of a century [1,65].

SRM strategies are supposed to "effectively, globally, rapidly, reversibly and inexpensively" [66] (p. 2) reduce global temperature levels [66–69]. They can be divided into space-based, atmospheric, and surface-based methods [12]. However, the only space-based method, aimed at installing space mirrors in the orbit between the Earth and Sun to hinder solar radiation reaching the Earth's surface (first idea by [70]), cannot be deployed unless costs are drastically reduced and major advances in technology are achieved and is therefore not being pursued further at the moment [12,71]. Even proponents of atmospheric SRM methods admit that those technologies exist only in theory, are not yet proven at scale, and are probably uneconomical if all costs are considered [31,72,73]. Based on this criticism, some highlight the need for more research on the respective SRM options [12,39,74,75]. In the following, we assess the potential positive and negative effects of the atmospheric SRM options, SAI, MCB, and CCT, as a basis for our following legal considerations.

- Stratospheric aerosol injection is also called "sunshade geoengineering" [76]. It aims at enhancing the Earth's albedo through the injection of aerosols such as sulphur dioxide into the stratosphere by high-altitude aircrafts or tethered balloons [12]. The gaseous sulphur dioxide (SO_2) oxidizes into light-scattering sulphate (SO_4), and thus, similar to when a volcano erupts, creating clouds that reflect more solar radiation back to space [74,77,78]. However, the large-scale technical implementation remains unclear and costs are likely to be much higher than often assumed [79,80]. Various multi-model results regularly demonstrate that the average surface near temperature could be restored close to pre-industrial levels, also in combination with CDR methods [81–85]. Apart from that, regional temperature imbalances, such as a temperature decrease in the tropics and an increase at the poles [86,87], as well as a reduced global precipitation, a disruption of the Asian/African summer monsoon, remaining acid ecosystems, polar ozone depletion, and negative consequences for terrestrial and marine photosynthesis are potential adverse effects of SAI [22,31,37,74,82,85,88–93] . Hong et al. [94] claim that the Atlantic Meridional Overturning Circulation alone might counteract cooling effects significantly. Bahn et al. [67] find that cooling effects will remain small and are rather artificial. Aerosols have a much lower lifetime in the atmosphere than greenhouse gases, and there are regional differences. This makes it challenging to determine the duration and intensity of aerosol injection. Additionally, global temperatures are expected to rise sharply if the injection of aerosols could no longer be continued with the same intensity [95–97]. Rabitz [98] develops scenarios for a sudden termination preventing greater harm, however only considering few variables and optimistically assuming that either multilateral cooperation or the economic strength of states will remain intact [98].

To avoid negative effects, SAI research proposes measures such as multiple injection locations, seasonal injections, a variation of the altitude and latitude of injections to minimize risks, or an additional injection of calcite along with SO_2 to avoid in particular ozone depletion [99–102]. Still, even multi-layer models bear uncertainties and are incapable of accurately reproducing highly complex natural interactions [85]. Thus, it remains unclear whether all risks of new SAI techniques are already known. So far, it remains highly unclear to what extent SAI can contribute a significant cooling effect and whether all potential adverse effects, especially for certain world regions, can be eliminated sufficiently, while it is certain that problems regarding the progressive degradation of ecosystems are definitely not addressed, beyond the prevention of damage done by rising temperature levels.

- Marine cloud brightening seeds low-altitude clouds by injecting sea salt particles into the atmosphere. These particles function as condensation nuclei and enhance the droplet number concentration of the cloud, particularly in tropical regions. The aim is to increase the reflection of shortwave radiation fluxes through more reflective stratocumulus clouds [103–105]. Further research reveals that even clear skies might enhance their reflexibility through sea spray injection [106,107]. The idea goes back to Latham [108] who particularly aimed to restore the polar ice shield and reduce the bleaching of coral reefs [104,109,110]. However, Baughman et al. claim that summer ablation rates in the Artic might not be slowed. Meanwhile, major changes in precipitation and atmospheric circulation patterns are likely to occur in the Western Pacific [16] (p. 78), [111]. Even though specific models show potential climate cooling effects [112] (p. 88), large uncertainties about the achievable effect remain, and the cooling seems to depend largely on the size and amount of the particles injected [107,113]. Injecting too little or too many particles might even lead to adverse climate effects [107,113]. Additionally, the aerosol–cloud interaction and a presumed high buffering property of the clouds against changes by aerosols are still poorly understood and hamper the prediction of achievable effects [12,113,114]. Besides unpredictable climate effects, globally altered water cycles are the main adverse effect expected [103,104,107,115]: On the one hand, globally reduced average precipitation is predicted, showing detrimental effects on vegetation growth [96,113]. This might significantly reduce terrestrial primary productivity in the tropics—such as in the Amazon Basin—in particular [96,107]. On the other hand, regional precipitation patterns might increase, particularly in lower latitudes [107]. Apart from all that, large-scale technological feasibility is at least questionable. In particular, the development of autonomous vessels or platforms that can be in permanent operation without depending on fossil fuels and that are reliable, even facing extreme weather events is still highly challenging [104].
- Cirrus cloud thinning is based on the fact that cirrus clouds produce a net warming effect, because they hold back terrestrial long-wave radiation [116]. CCT therefore aims to reduce this warming effect by thinning the clouds. By seeding ice nuclei into the clouds, larger ice particles are expected to grow. Reaching a certain size, they sediment out of the clouds and reduce the thickness and life-time of cirrus clouds [12,117]. Seeding is foreseen via aircraft or autonomous drones. Potential cooling effects are predicted to have a more direct effect on a specific region—in contrast to SAI or MCB [116,118]. However, cooling effects are again highly uncertain and prone to affect other regions as well. Firstly, they depend on the geographical distribution of cirrus clouds—tropical regions with anvil cirrus clouds are excluded [119–121]. Secondly, the parameters of ice nucleation and effectiveness of injected ice particles into potentially inhomogeneous and chemically variable cirrus clouds also remain largely unknown in middle and high latitudes [116,122,123]. Additionally, overseeding cirrus clouds might even cause a countereffect and lead to a global net warming [116,124]. Finally, the occurrence of negative effects on precipitation patterns or side effects of using toxic bismuth tri-iodide as an effective seeding material instead of sea salt cannot be excluded either [12,123]. In particular, these possible adverse effects, which could lead to a further increase in warming instead of cooling, question the whole technology approach significantly.

All described atmospheric SRM methods have in common that—so far—they exist only as models. All of them entail major uncertainties that do not allow precise predictions on the extent of the achievable effects on the Earth's temperature balance. The expected adverse effects range from a globally or regionally changed precipitation regime to regional temperature imbalances and negative consequences for terrestrial and marine photosynthesis. In particular, by influencing rainfall or the creation of potential drought- or flood-causing clouds, regional inequalities might be amplified as access to food and water for millions of people might be threatened [69,125,126]. It is an almost impossible challenge to accurately predict these possible negative impacts. Hence, transboundary impacts and geographical heterogeneities are expectable for each of the technologies—even if it is only implemented for the purpose of scientific research. The effects on some regions will be more severe than on others [22].

There are some findings that suggest positive side effects and the possibility of resolving some of the crucial issues, such as the question of terminating the use of a technology [98], or a way to conduct scientific trials to scale without the possibility of inflicting permanent or large-scale and transboundary harm [78]. However, in the following, this paper takes a look at the legal implications rather than (technological) feasibility as such. As will be discussed below, requirements of, e.g., the precautionary principle are to rule out harm to a reasonable extent. Therefore, only if all side effects can be estimated and subsequently eliminated or managed, a technology becomes viable. It is not the purpose to weigh positive effects against negative ones, but to identify possible risks and weigh them against alternative paths of action.

4. Results and Discussion: Legal Analysis Regarding Geoengineering in International Law and Human Rights

This takes us to our legal analysis on international environmental law and human rights, even though there is no specific "geoengineering protocol". Atmospheric SRM technologies are generally not in a state of deployment yet. However, already pursuing research to assess their effects might possibly lead to large-scale impacts [12,13,75,126,127]. Therefore, when analyzing the existing regulation, we have to consider both research and deployment options.

4.1. Assessment of Potential Legal Starting Points to Regulate Geoengineering and in Particular SRM

The Convention on Biological Diversity has produced the most explicit legal regulation of geoengineering. The CBD took decisions critical of geoengineering technologies (COP 10 Decision X/33 2010 and COP 11 Decision XI/20 2011) in response to the fact that most of the potential adverse effects of both—CDR and SRM—geoengineering approaches will probably occur directly or indirectly on biodiversity and ecosystems. The decisions aim to prohibit "climate-related geo-engineering activities that may affect biodiversity, until there is an adequate scientific basis on which to justify such activities and the associated risks" (COP 10 Decision X/33 W, a follow-up on COP 9 Decision IX/16 C targeting ocean fertilization specifically). In other words, any activity must meet the scientific standards called for by the precautionary principle (see below). The CBD further specifies that the prohibition of respective geoengineering activities applies to "any technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale" (COP 10 Decision X/33 W, footnote 3). Thus, experiments which might also have adverse transboundary impacts and are not of small scale are included, unless conducted in a controlled setting. The decisions are based on Art. 8 especially lit. d, e, h CBD, which aim to preserve ecosystems, local occurrences of species, and their required environments and to avoid alien and harmful influences on ecosystems. As seen above, to date, those adverse effects on ecosystems cannot be fully assessed with regard to large-scale atmospheric SRM technologies. Therefore, the CBD decisions rule out their further exploration. Although the legally binding nature of the CBD is undisputed, there is an ongoing debate about the legal status of decisions by the Conference of the Parties (similar to the binding nature of agreements within the climate regime, which is discussed in [6]). Therefore, the question arises if there are more definite regulations in other parts of international environmental law.

Other conventions and treaties might in part apply to atmospheric SRM deployment or field research within their specific field. The UN Convention on the Law of the Sea (UNCLOS) safeguards in Art. 192, 194–196, 212 marine environments and the atmosphere above the sea from pollution and regulates substances ejected by vessels. The Vienna Convention for the Protection of the Ozone Layer could generally be thought to apply, as it requires member states to take action to prevent "adverse effects" (Art. 2 Vienna Convention for the Protection of the Ozone Layer) on human health and the environment caused by activities in the ozone layer. The Vienna Convention for the Protection of the

Ozone Layer prohibits the injection of substances into the atmosphere that might cause damage to it. Based on the findings above, damage cannot be ruled out at the moment and is even probable to occur, concerning SAI in particular. However, the Vienna Convention mostly aims to establish cooperation among member states and requires them to takes action "[i]n accordance with the means at their disposal and their capabilities" (Art. 2 para. 2 Vienna Convention for the Protection of the Ozone Layer). The Montreal Protocol on Substances that Deplete the Ozone Layer contains measures to prohibit the injection of substances harmful to the ozone layer. However, hydrogen sulphide (H_2S) and SO_2 used for SAI are not included in the Annex listing relevant substances [128]. Even though the Environmental Modification Convention (ENMOD) explicitly regulates the modification of weather and the deliberate modification of natural processes, its scope is limited to military and hostile use and is therefore not applicable to geoengineering. Likewise, other treaties that are topically related, such as the London Convention and London Protocol (LC/LP) on the dumping of waste and other matter at sea, the Geneva Convention on the Long-Range Transboundary Air Pollution, the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and other Celestial Bodies, or Convention on International Civil Aviation, do not offer a general normative basis to determine a general framework for atmospheric SRM and have been reviewed elsewhere in more detail [66,129].

Therefore, the next look for regulation leads to the UN Framework Convention on Climate Change and the Paris Agreement. It has often been discussed that the PA is hardly ecologically effective, because it does not provide concrete enforcement mechanisms and global governance instruments such as a binding global emissions trading scheme [6,130–134]. This, however, is not the relevant point in this case. Neither is the fact that the PA (and perhaps also the UNFCCC) contains a number of provisions that merit discussions whether they are legally binding at all, and how very specific reduction targets for individual states are not explicitly listed [130,134–137]. In any case, however, the basic target commitment and the system of nationally chosen reduction targets based on this target commitment are binding. This can be found in Art. 2, 3, 4 PA. It is undisputed that the agreement as such is constructed as a binding international treaty [136]; and in the case of Art. 2–4 PA specifically, the wording does not indicate that it is not meant to be binding [6,130,132,138]. While modal verbs such as "will" or "aim" can be interpreted as merely non-binding announcements, the words "are to" and "shall", as used in Art. 3, 4 PA, clearly indicate the legally binding nature (as in [136]). This alone is referred to in and is relevant to this paper. Legally binding force must not be confused with enforceability; here, we will not discuss the complicated question before which national, EU, or international law court PA obligations can be ruled on (for example, Art. 2 PA plays a role in an ongoing climate lawsuit before the German Federal Constitutional Court; for background [2]).

The PA does not explicitly mention geoengineering. This could lead to the conclusion that it is simply not applicable and contains neither a mandate nor a prohibition of geoengineering in general, and of atmospheric SRM in particular. However, there are some textual and systematic arguments from other norms of the PA that are not favorable of atmospheric SRM. The following questions are: (a) whether an overshoot is allowed or not, (b) whether the risks of geoengineering and of specific SRM approaches in particular rule out these options or not (at least as long as other options such as emission reduction are feasible), and (c) whether either technological large-scale interventions or the enhancement of natural sink in the land-use sector by changing agricultural and forestry practices, rewetting peatlands, etc., prevail in terms of removing carbon dioxide that remains even in a zero-fossil-fuels world.

First of all, there is a clear textual argument that the PA does not allow for overshoot scenarios, which makes an important basis of the discussion about geoengineering, especially regarding atmospheric SRM measures void. Taking Art. 2 para. 1 PA literally [6], "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels …" does not mean being able to exceed the temperature limit to return to it later on. This does not generally rule out SRM technologies, even so it is questionable whether the risks of rapid temperature increase when halting SRM implementation (as described above) are within the margin of the provision. More clearly, however, Art. 4 para. 2 and 3 PA call for domestic mitigation efforts at the highest level of ambition. Thus, climate agreements do not leave room for using atmospheric SRM approaches instead of mitigation (and adaptation) measures.

In addition, there is a clear textual argument that large-scale technological interventions, atmospheric SRM in particular, is not intended as a key climate protection measure: The PA aims to reduce GHG concentrations and to reach a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" (Art. 4 para. 1 PA; on the legal relationship between Art. 2 and Art. 4 PA, see [2,6]). However, SRM in general produces neither emissions reduction nor removal by sinks. Furthermore, Art. 2 UNFCCC—as the basis of the Paris Agreement—calls for a "stabilization of greenhouse gas concentrations in the atmosphere", not for a compensation by means of SRM. There is, however, no explicit prohibition ruling out that SRM might play an additional role, e.g., in conjunction with mitigation [139]. However, since it has no place in contributing to reaching the PA targets, this role would need to be temporary and marginal—raising the question of why to resort to it at all.

4.2. Discussion—Why Emission Reduction and Increasing Natural Sink Capacities Prevail

The notion against focusing on atmospheric SRM is emphasized by a bundle of textual and systematic arguments from PA in connection with human rights and the precautionary principle that shows that reduction fossil phasing-out, etc., and increased natural sinks in the land-use sector prevail against large-scale technical interventions such as atmospheric SRM approaches—and which underline that an overshoot is not permissible from the human rights perspective and the potential unpredictable negative consequences of an overshoot. These textual and systematic arguments make the case for an ambitious level of climate protection by means of the most effective and the most riskless measures—and for those measures such as wetland management that are required anyhow due to environmental challenges other than climate change. These arguments, containing various legal elements, are as follows:

- Art. 2 para. 1 PA sets a legal obligation for preventing dangerous climate change meaning limiting global warming to well below 2 °C and pursuing efforts to stay below 1.5 °C. Elsewhere [6], three implications of this were shown: (a) Although often overlooked, this obligation is legally binding, as follows from Art. 3 and 4 PA. (b) This obligation implies that the target must be met as safely as possible. Probabilities of meeting the target of only 50 or 66%, as envisaged by the IPCC reports [1,17], are not sufficient [see Chapter 3.1]. Even more so as the underlying assumptions of the IPCC also tend to be too generous. Therefore, net zero emissions must be achieved promptly (in a maximum of two decades) on a worldwide scale. (c) The wording of Art. 4 PA makes it clear that this norm is subordinate to Art. 2 PA, because Art. 4 PA merely serves to implement Art. 2 PA. For this reason, the wording of Art. 4 PA, for net zero emissions any time after 2040, is superseded by Art. 2 PA.
- Furthermore, human rights as rights to freedom (as stated in various binding international treaties, especially the International Convention on Civil and Political Rights and the International Convention on Economic, Social and Cultural Rights) logically imply the right to the elementary preconditions of freedom. These in turn include a relatively stable global climate and environmental conditions allowing for maintaining the basics of human livelihoods [2,6,140]. Admittedly, the freedom of enterprises and consumers, impeding a more ambitious climate policy, has also to be taken into account. However, although it is correct that balancing human rights obligations to climate change is prima facie left to political margins (for instance, due to the contradicting freedom rights of enterprises and consumers), which is only limited by those balancing rules that have to be complied with, one of these rules states that political margins of decision-making end where political action or non-action will endanger the liberal-democratic system as such. Precisely this is the case if climate change is not mitigated appropriately. This is why human rights contain a strong obligation towards climate protection in accordance with Art. 2 para. 1 PA [2,6].

- In addition, general principles of international law, here the precautionary principle, remain, determining the corridor in which SRM activities might at all take place. Precaution means taking measures in view of long-term, cumulating, or uncertain damages [2,38,141–144]. This does not totally prohibit the pursuit of an action, which bears the chance of causing irreversible harm (since precaution also implies balancing different risks and opportunities, and even daily life entails irreversible risks) when it comes to huge risks. Climate change exceeding the objective of Art. 2 para. 1 PA will lead to such irreversible negative consequences on a global scale and therefore needs to be mitigated. Even if disputing the role of the precautionary principle in general [145,146], it is clearly codified on several levels in national, EU, and international law, i.e., in Art. 3 para. 3 UNFCCC, in the Treaty on the Functioning of the European Union (TFEU) in Art. 191, or in Art. 20a of the German Constitution (Grundgesetz). Moreover, precaution is included in human rights. Basic rights protect not only against certain dangers, but also against future dangers if the latter is irreversible at the moment of occurrence; and exactly this is the case with climate change. If that were not the case, the protection provided by basic rights would run empty. Human rights thus contain a precautionary principle, even beyond codification [2,6,140]. The connection to human rights makes it clear: the bigger the impending damage in its occurrence, the more ambitious the necessary protection measures have to be.
- Another principle of international environmental law is the preventive principle, which calls for early action and in view of transboundary environmental damage. While the precautionary principle contains the responsibility to take action even in view of scientific uncertainty, the preventive principle calls for refraining from an action that might directly lead to damage, or stop it as soon as consequences become apparent [141,147]. This implies that counteracting global warming by employing SRM is not sufficient, as it does not eliminate the cause of the anthropogenic damage. In addition, atmospheric SRM technologies at the current state of research bear the risk of causing additional harm themselves, or might have highly uncertain side effects [91,148,149]. The preventive principle, as part of the Rio Declaration on Environment and Development (A/CONF.151/26 (Vol. I) of 12 August 1992), is soft law. However, the principle has been reiterated in the preamble of the UNFCCC and in other treaties mentioned above. It has also been invoked by the International Court of Justice (ICJ Reports 7 at 78, para. 140).
- One more principle has to be taken into account. The international law principle—or rather the concept—of sustainable development consists of three parts: intertemporal equity, sustainable use of natural resources, and the integration of environment and development [141,147] (on details and further implications [2]). Climate change will have dire consequences on the living conditions for future generations. Its successful mitigation is therefore required in terms of intertemporal equity. Atmospheric SRM approaches might impair this principle, because they might delay mitigation action such as phasing-out fossil fuels, etc., and prolonging the process of emission reduction [41]. This might put additional strain on future generations [46,96]. On the other hand, a—thus far, however, missing—broad social discussion on the risks of large scale atmospheric SRM approaches might spur commitment to not rely on those technologies and avoid them by strict mitigation measures [75,150]. In any way, sustainable use of natural resources calls for the quickest possible omission of all uses of fossil fuels, which, again, might be prolonged if atmospheric SRM technologies are (even additionally) communicated as a reliable option to be used. As for the chances of development, one could argue that respective SRM approaches will buy necessary time for development particularly in developing countries. However, chances are that adverse impacts, both transboundary and direct, of atmospheric SRM will occur exactly in regions with high vulnerability, such as tropical forests and deserts. The concept of sustainable development, though quite far-reaching, has no concrete legally binding basis; however, it is the core concept of the UN Conference on Environment and Development from which the UNFCCC and the CBD emerged (among others). It therefore has a strong normative value in setting a standard in which climate protection is to take place [151,152].

- All of this implies that very ambitious climate protection is required. A drastic reduction in GHG emissions including largely underestimated non-CO_2 emissions [50,153] is necessary alongside the enhancement of natural sinks by sustainable land-use management regarding agriculture, forestry, and wetlands. These mitigation measures—without overshoot—are the option that (a) is more certain than large-scale technological geoengineering in meeting the obligatory climate targets and (b) poses fewer open questions with regard to side effects, which in turn, endanger the respective human rights to the elementary preconditions of freedom, such as life, health, and subsistence [154]. Furthermore, (c) the human rights protection and the CBD require drastic mitigation measures anyhow, because the cause of biodiversity loss, pollution, disturbed nutrient cycles, etc., is more or less the responsibility of major polluters as it is climate change: fossil fuels and (industrial and large-scale) livestock farming. Therefore, focus should lie on phasing-out fossil fuels globally in all sectors and changing the agricultural sector fundamentally, particularly livestock farming [2,7,143,155,156]. On the other hand, it already became clear that the whole Agriculture, Forestry, and Other Land Use (AFOLU) sector contains the largest sink capacities. Forest restoration and sustainable forest management (under certain conditions that avoid trade-offs also afforestation and reforestation) [24,25,157–159], enhanced carbon sequestration in soils, stimulated by altered agricultural practices, i.e., agroforestry catch cropping, etc. [144,160–162], and rewetting peatlands [163] are potential measures to enhance these capacities (on policy instruments for the land-use sector see in detail [5,6,9,144]). Even if certain trade-offs must also be taken into account, end-of-pipe solutions such as large-scale geoengineering measures do not solve other environmental problems, such as the progressing ecosystem degradation and acidification, which are also caused directly or indirectly by using fossil fuels. Using atmospheric SRM technologies instead of the aforementioned mitigation or adaptation measures might increase the vulnerability of those who are already most exposed to the negative consequences of global warming specifically (e.g., indigenous people [164]), but also other environmental problems in general [22,165,166]. Apart from that, as GHGs remain in the atmosphere multiple times longer than injected aerosols, SRM measures require future generations to continue the injections permanently or live with the costs of the hugely increased pace of global warming after ceasing them [75]. Furthermore, it is likely that the development required to make atmospheric SRM technologies operational and to provide a long-term risk assessment will most likely take too long for any large-scale deployment to meet the requirements of the PA (zero emissions within the next two decades). Even if this path were to be pursued, the cooling effect, which can be achieved by atmospheric SRM measures, has not been quantified yet and is subjected to high uncertainties. Measures targeting fossil fuels (and livestock farming, etc.) will have risks and consequences themselves, at least if they include frugality and beyond technological strategies (on frugality options alongside technological strategies as well as on their consequences [2,160,167–171]; especially on livestock see [63,159,172,173]). However, these risks are lower and therefore preferable to the significant risks and uncertainties associated with atmospheric SRM technologies in light of considerations of human rights and the precautionary principle [31,174–176].

This leads to the conclusion that atmospheric SRM technologies are not suitable to be used as a measure for climate protection. Technical large-scale interventions to enhance sinks or to directly alter the Earth's radiative energy in general should not interfere with efforts aimed at less controversial solutions, which mitigate GHG emissions and compensate nature-based for residual emissions [6,41,177]. Addressing climate change requires omitting its causes and drivers. There are some technologies that are farther along in the process of technological development and pose fewer risks. However, in view of the urgency of the issue and the danger for human rights and their preconditions, relying on atmospheric SRM technologies is not merited. With regard to policy instruments for implementing these strategies, economic instruments that relate to major polluters—fossil fuels and livestock products—in line with the PA and the CBD remain the most promising solution [5,6,160,178].

4.3. Options of Regulating Atmospheric SRM Research

Despite the necessary focus on emission reduction and an increase in natural sinks, atmospheric SRM regulation is still needed regarding research and field experiments [179–181]. At least theoretically, it is possible that sufficiently tested and best possible improved technical geoengineering approaches might be needed at some point in the future in order to protect human rights. This becomes relevant if mitigation policy fails. Therefore, research continues to make sense in principle. Many proposals have been made as to how a regulation could be shaped and what it should entail. In the beginning, the debate has been led by natural scientists who look at scenarios and aim to fill an emissions gap [14,31]. Recent years have also brought about more research from specific policy perspectives [128,182]. The proposals cover a wide variety of objectives between enabling an allegedly necessary technology, merely creating a set of rules, and banning SRM technologies overall [183,184].

Due to the liberal-democratic principles of democracy and balance of powers [2,185], the mandate to decide which technology is experimented on and ultimately deployed has to be in the hand of (democratically elected) politicians and neither up to scientists nor to private actors. At the moment, non-state actors with research interests and the respective funding play a decisive role in terms of atmospheric SRM—at least in the US—and thus need to be covered by a regulation [32,128,183]. As high-tech, large-scale, finance-intensive technologies that seemingly allow for business-as-usual behavior, atmospheric SRM development triggers the interest of fossil-based industries and wealthy technology enthusiasts [186–188]. Trying to create a steering effect by directing public funding to the desired research, e.g., by the World Bank, will probably not be very effective as there are strong private interests in pursuing atmospheric SRM enabling research, which does not depend on public funding [66,72,129,186]. A major problem in regulating respective research is that experimental research on geoengineering technologies amounts to the practical application of technologies such as atmospheric SRM. In other words, it may be difficult to come to valid natural scientific results while at the same time not risking large damage. What is now required by the precautionary principle and human rights would then be allowed by a respective treaty—at least with the current state of technology. In this respect, the scope for further natural scientific research remains small.

As we are dealing with evolving technologies, the more specific an applicable regulation is, the higher is the frequency in which the technology has to be adapted to a new state of research. To prevent the necessity of a constantly repeated legal examination, many approaches resort to rather general criteria, because securing and creating collective structures of decision making on a case-by-case basis ex ante is regarded as most promising. The advantage of this approach is that it prevents the need to regulate every single technological approach individually. Individual regulation would immensely inflate the regulation and open it up for loopholes and grey-areas as research progresses. Furthermore, there is consensus in the reviewed literature regarding: creating transparency of research and other geoengineering projects, impact assessments, liability, international cooperation, and broad participation in decision-making regarding specific geoengineering techniques [12,128,166,182–184].

In the analysis of existing legislation, we have seen that there are different potential regimes in which a respective geoengineering regulation might be placed. One is the climate regime, e.g., as an amendment to the PA. This would place SRM among other climate protection requirements and instruments and imply a setting that would enable SRM to be a new technology. However, as seen, it cannot be the goal to free the way for atmospheric SRM becoming a recognized measure for climate protection. Another option would be to pass it as a protocol under the CBD. In this context, it would be placed in a key field that might be negatively affected by atmospheric SRM technologies. Both of those options would make the regulation legally binding under international law; however, with very weak enforcement mechanisms and only binding to states that agree to it (excluding, e.g., the U.S. that is currently at the forefront of atmospheric SRM research, see [188]). In any case, it seems to be most sensible to create a separate body that will specifically deal with approving SRM requests and that should also have the power to enforce violations, e.g., via arbitration.

5. Conclusions

This paper has shown that there is a strong legal obligation for ambitious climate protection without overshoot, which is based on human rights and the Paris Agreement. While the emissions gap leads to a growing number of scientific scenarios and climate projections that either seek to cool the climate in the aftermath via (atmospheric) SRM measures or resort to negative emissions that require technical large-scale interventions to enhance sinks via CDR approaches, they have no normative character. Regarding the effects and risks of large-scale geoengineering technologies and, in particular, atmospheric SRM approaches, it was shown that the considered technologies are currently associated with potentially high and largely incalculable risks and uncertainties regarding their effectiveness. Due to these points—and due to the need to reduce fossil fuels and livestock farming anyhow (because of biodiversity protection, etc.)—these classical mitigation strategies are the legally required measure against climate change leaving at best a marginal role for respective SRM technologies. For the same reasons, to enhance natural sink capacities in the land-use sector, e.g., by seeking for a sustainable management of forests, wetlands, and enhanced agricultural practices prevails against other options to remove residual emissions that remain even in a world with zero fossil fuels in all sectors and less livestock farming. Moreover, it proves difficult to conduct any kind of field experiment concerning atmospheric SRM with reliable and sufficient results as even small-scale experiments in this respect might have transboundary and irreversible effects on the environment and on livelihoods. This requires further discussion. Still, there is the need to close the regulation gap regarding research and possible deployment of geoengineering and, in particular, atmospheric SRM technologies. Therefore, some regulatory options for this in international law were discussed briefly, proposing an international body to conclude.

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