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SRM on the table: the role of geoengineering for the stability and effectiveness of climate coalitions

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Abstract

Geoengineering, including solar radiation management (SRM), has received increasing scrutiny due to the rise of climate extremes and slow progress in mitigating global carbon emissions. This climate policy option, even as a possibility, can have consequential implications for international climate governance. Here, we study how solar engineering affects the effectiveness and stability of a large set of regional coalitions through numerical simulations. We posit a requirement in terms of global political or economic power and analyze the exclusive membership coalition formation process when coalitions jointly decide on geoengineering and mitigation. We show that geoengineering can provide incentives for cooperation and partially solve the typical trade-off between stability and effectiveness of climate coalitions. However, temperature reduction mostly comes from deploying SRM within the coalition rather than from further emission reductions, thus exposing the world to relatively large-scale deployment of SRM with as of today uncertain potential side effects and risks.

Keywords Geoengineering · Mitigation · Coalitions · Stability

1 Introduction

According to the latest IPCC report (IPCC 2021), it is only possible to avoid warming of 1.5 °C or 2 °C if massive and immediate cuts in greenhouse gas emissions are made. International cooperation is crucial for this matter; thus, since the early papers by Barrett (1994), Carraro and Siniscalco (1993), Chander and Tulkens (1992), and Maler (1989), there has been an increasing number of publications that analyze the formation and stability of international environmental agreements (IEAs) using game theory and numerical models. The common result found is that there is a trade-off between the stability and the effectiveness of coalitions.

The model code and data for the RICE50+ model including the SRM module is available at https://github.com/witch-team/RICE50xmodel The results files and code for the analysis and figures is available at https://piergiuseppepezzoli.github.io/SRM-on-the-table/.

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In the absence of additional policies, stable coalitions tend to be small and achieve little, due to a lack of internal stability of larger, more ambitious coalitions (Lessmann et al. 2015). Most studies analyze only static definitions of stability such as Cartel (Internal/External) stability (D'Aspremont et al. 1983; Carraro and Marchiori 2002; Finus et al. 2006) and γ-core stability (Chander and Tulkens 1995, 1997; Chander 2007), but there are some contributions including Heitzig et al. (2011) which look instead at a dynamic approach. Bréchet et al. (2011) find that economic transfers can make the grand coalition stable in the γ-core sense, but it is never the case in the Internal/External sense; only smaller coalitions, where there is less to free-ride about, are found stable with transfers. Moreover, homogeneity among the members of a coalition appears to help the potential internal stability of a coalition, but the global outcome in terms of environmental performance reached by these homogeneous coalitions is far less attractive compared with the heterogeneous world efficient allocation. Finus (2008) analyzes the design options for international agreements using a numerical model. Nordhaus (2015); Paroussos et al. (2019) investigate the effects of exclusive membership and climate clubs analytically. Uncertainty about climate damages can improve cooperation, as found in Barrett and Dannenberg (2012) and Emmerling et al. (2021), but without a clear idea of when the catastrophic consequences will happen the stability fails.

Since current efforts are vastly insufficient, several geoengineering methods have been discussed as a possible complement to emission reduction (Keith 2000). In this paper, we focus on one of the commonly proposed geoengineering techniques, solar radiation management (SRM) and its implementation by ejecting a large amount of sulfur dioxide (SO2) into the atmosphere, causing a rapid drop in temperature (Keith 2000; Crutzen 2006). This technology has arguably the largest impacts as a disruptive technology both due to its relatively low cost and high efficiency in reducing the global mean temperature.

The scientific principles behind geoengineering technologies are well established (NRC 2015), and it has been suggested that the cost of geoengineering could be so low compared to traditional mitigation strategies that they would make climate change irrelevant (Barrett 2008). There are however large uncertainties regarding the effectiveness, side effects, and potentially unforeseen consequences of geoengineering. Interventions at a large scale may run a greater risk of disrupting natural systems, resulting in a dilemma that those approaches that could prove highly cost-effective in addressing extreme climate risk might themselves cause substantial risk. This dichotomy has been addressed in Weitzman (2015), who coined the term “gob” (good or bad) to describe geoengineering.

Since the strategic component of climate policies is crucial, the problem is often framed within a game theoretic framework. Moreno-Cruz (2015) studies the dynamic nature of the SRM-mitigation trade-off in a sequential two-stage game and finds that highly asymmetric impacts are an important driver of potential over-provision of SRM. Urpelainen (2012) considers a simple two-period deterministic model, showing that the availability for SRM in the future can increase mitigation efforts at present since it can hurt other countries. Millard-Ball (2012) considers the formation of a climate agreement about mitigation, where SRM is a private good with a negative externality. He shows that a credible threat of unilateral geoengineering may in fact strengthen global mitigation and climate cooperation. Manoussi and Xepapadeas (2017) study a differential game between two heterogeneous countries, finding that countries with higher benefits/lower costs will engage more in using SRM. Goeschl et al. (2013) analyze the long-term inter-generational trade-offs due to the possibility of SRM and finds it is possible for optimal abatement level to exceed the level that society would rationally provide in the absence of SRM R&D, while Quaas et al. (2017) consider the dynamics including the non-cooperative decision on whether or not to engage in research on SRM in the first place. They find that SRM research increases the likelihood of deployment (“slippery slope"), and derive conditions that it decreases abatement effort in expectation ("moral hazard"). Moreno-Cruz and Smulders (2017) also develop optimal and non-cooperative SRM facing impacts from temperature increase and carbon concentrations (using a more complex carbon cycle) in a one-stage game, finding that even when geoengineering is cheap and has little harmful side effects, it can never fully substitute for mitigation.

One of the key results often associated with an almost costless geoengineering is that, in contrast to the free-rider problem posed by climate-change mitigation, the actual governance challenge associated with SRM deployment becomes a free-driver problem (Weitzman 2015): the pure non-cooperative Nash equilibrium outcome would be that the country with the strongest interest in cooling the climate would unilaterally adjust the global temperature to their preferred level (Barrett 2008, 2014).

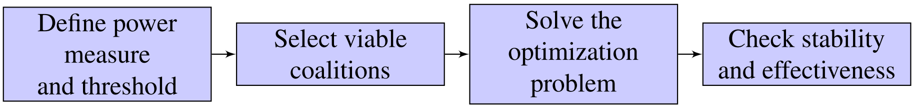
However, besides the (comparably minor) implementation costs, there is a strong social component that needs to be overcome for a successful implementation (Low et al. 2022), and more importantly, an operation of this scale would be under the close watch of the whole world. Following this reasoning, Ricke et al. (2013) suggest that only a sufficiently powerful international coalition might be able to deploy solar geoengineering. They propose an exclusive coalition game where a power threshold is necessary for implementation and countries ally to decide SRM levels. They show that regional differences in climate outcomes create strategic incentives to form coalitions that are as small as possible, while still powerful enough to deploy solar geoengineering. Rickels et al. (2020) study instead an open membership game, finding that countries have a strong incentive to be part of a global agreement on SRM in order to have their interests reflected in the decision about the globally efficient level of SRM deployment, suggesting that the grand coalition would be the likely outcome. Heyen and Lehtomaa (2021) propose a framework to analyze dynamical coalition formation instead of a static one. These approaches, however, exclude traditional strategies of mitigation and have been criticized over time (Finus and Furini 2022) because they fail to grasp more complex relationships that spur from the interaction between the two.

In this paper, we extend the concept of Ricke et al. (2013) by analyzing an exclusive membership coalition process where coalitions decide not only geoengineering deployment but also mitigation. Therefore, we are able to compare the effectiveness of SRM and mitigation in coalitions and also their respective stability using different notions of stability concepts. We also introduce elements of political feasibility of SRM interventions by assuming they require a minimum power to be enacted.

2 The coalition formation game

To model SRM, we follow Ricke et al. (2013), which stipulates a minimum power requirement for its implementation, denoted by θ_{SRM}. We retain the closed membership coalition process, but extend it to include joint decision-making on both geoengineering deployment and mitigation policies.

We analyze a two-stage game: in the first stage, a close membership geoengineering coalition is formed. This coalition will remain fixed (since we do not focus on dynamic coalition formation) and act as a single entity in the second stage, when a non-cooperative climate game is played. A cost-benefit analysis is run, finding a Nash Equilibrium. The SRM coalition seeks to maximize the sum of utilities of its members, against all the remaining players, who act as singletons. For the numerical results of the second stage, we will make use of an integrated assessment model which is described in detail in Section (3). We solve the game by backwards induction. We use total GDP in 2020 as a proxy for power, select all the viable coalitions that meet the power threshold θ_{SRM}, and solve the cost-benefit optimization problem for each. We then assess both internal stability and γ-core stability of the coalitions and their effectiveness in achieving climate goals based on the optimization results.



We also perform robustness tests by performing a sensitivity analysis on SRM collateral damage levels (δ_{SRM}, ranging from 1 to 3% of GDP, based on Goes et al. (2011)) and on the power threshold necessary for SRM implementation θ_{SRM} (50% or 33% of the global power). Since the number of feasible coalitions grows exponentially, we aggregated the model regions to obtain a feasible and yet relevant set of homogeneous blocks or regions to run the analysis with. First, we aggregate the 57 regions that were used to the generate initial numerical results into 17 larger regions that have the option to form coalitions. Moreover, we limit our analysis to minimal winning coalitions (MWCs), that are winning in the sense that the combined power of their members is above a specified threshold, and minimal so that if any member leaves, they cease to be winning. This confines our analysis to the coalitions that are powerful enough to implement SRM, while at the same time focusing only on coalitions without members which are not required to meet the power threshold. A recap is shown in Table 1.

The basis for our selection is derived from the findings of Ricke et al. (2013), which indicated that in a game of optimal temperature setting ("thermostat game") with closed membership, only MWCs are formed. In their paper, this came from the fact that adding new members meant compromising on desired SRM levels. In our study adding mitigation policies, a new member also means higher cooperation costs, so we expect this result to hold true. To further validate this decision, we assessed the external stability of these coalitions within a closed membership game. This assessment necessitated a substantial computational effort, as we had to ensure that for each coalition, at least one member would not be interested in recruiting a new coalition member due to the potential harm caused by their arrival (Hou et al. 2020). This process involved simulating a new set of coalitions for each possible MWC, with non-members added one at a time, and then comparing the new utilities of all the old members and the new joiner with the ones they had with the initial minimal coalition structure. We limit this assessment to the scenario where $\theta_{SRM} = 50\%$, $\delta_{SRM} = 3\%$ (yielding 16,362 additional model runs). Our findings indicate that all the coalitions are externally stable, meaning that there is no incentive to form coalitions that are larger than the minimal winning ones. This confirms the validity of the MWC assumption.

For similar computational complexity reasons, we also decided to prioritize the analysis of γ-core stability over internal stability. γ-core stability assumes that when a member leaves the coalition, the coalition breaks down. It is assessed by comparing the utilities of members inside the coalition against the case where no coalition is present and all players are singletons. While this assumption could be considered a strong one, it still seems not too unrealistic,

Table 1 Number of total, winning, and mininal winning coalition

	Total coalitions	Winning coalitions	MWC
`SRM = **50%**	131,055	65,529	1853
`SRM = **33%**	131,055	104,284	1516

also since non-coalition SRM deployment could result in counter-engineering (Heyen et al. 2019). Moreover, note that since our hypothesis of a minimum power requirement for SRM implementation, geoengineering is only available for the winning coalition and not for the singletons. This makes SRM an incentive for coalition formation, partially offsetting cooperation costs. Internal stability instead assumes that the coalition continues to exist even if a member leaves and is much more complex as it requires all potential break down resulting coalitions of any coalition. To assess it, we perform additional runs for each coalition, where we exclude one by one each member and compare its utility inside the coalition against the one as a singleton. We implemented this only in the $\theta_{SRM} = 50\%$ scenario, which required 15,139 additional model runs. Note that, owing to the imposed constraint of minimality and the prerequisite of power for SRM, the availability of geoengineering is exclusively limited to the initial MWC, similar to before. Therefore, any member who decides to withdraw from the coalition will forfeit all the benefits derived from it.

3 The model

In this section, we describe the numerical model that we use to provide a real-world quantification and to answer governance questions that cannot be tackled by theoretical analysis alone. A numerical quantification is necessary to provide an analysis of real-world policies since many of the analytical findings rely on arbitrary parameters to convey their results, whereas in a realistic scenario, we would expect them to assume either specific fixed values or come from some known distribution. To do this, we expand with equations and code the integrated assessment model (IAM) RICE50+ (Gazzotti et al. 2021). This model is a regionalized version with up to 57 regions/players of the well-known DICE model from Nordhaus (1992) and integrates many different aspects of human knowledge to capture how human development and society interact with the Earth system. The model allows performing a cost/benefit analysis in a cooperative way with a global social planner or in a non-cooperative way, finding a Nash equilibrium through an iterative, open loop algorithm. We also implement an option that allows partial cooperation, with the presence of coalitions of regions that act as single players against each other in a non-cooperative manner. Players maximize their Balance Growth Equivalent (BGE) (Stern 2014):

$$\max \sum_{n \in Coalition} BGE_n$$

$$BGE_n = \left(\frac{\sum_t l_n(t) * (1+\rho)^{-t} * C_n^{CAP}(t)^{1-\mu}}{\sum_t l_n(t) * (1+\rho)^{-t}} \right)^{\frac{1}{1-\mu}}$$

which is based on consumption per capita $C_n^{CAP}(t)$ [US-\$ (2005, PPP)], the population $l_n(t)$ (million people), the pure rate of time preference (ρ), and the elasticity of marginal utility of consumption $\mu = 1.45$.

Climate impacts are computed implementing a growth impact function based on the empirical panel estimation of Kalkuhl and Wenz (2020). Their global mean estimated projects GDP losses of around 11% for a global temperature increase of 3°, which is roughly in the middle of two recent global studies, on meta study (Howard and Sterner 2017) and model-based damage function estimation (van der Wijst et al. 2023). The climate-econometric damage function based on regional temperatures allows to capture impact differences at the country level, which is crucial for this model. This damage specification thus captures global heterogeneity and lies within the range of global estimates in recent assessments, even though conceptual and methodological issues remain (Newell et al. 2021).

The damage function depends only on regional mean temperatures and its change over time, which we downscale from the global temperature anomaly for all countries based on a temperature downscaling using the Model mean of the CMIP5 database (Taylor et al. 2011). The global temperature changes are based on a recalibrated version of the DICE carbon cycle and two-layer temperature module.

We add a module to this model, which integrates $SRM_n(t)$, a variable that indicates the amount of sulfur dioxide (measured in teragrams of sulfur [TgS] per year) injected in the atmosphere by each player n at each time step t. We assume that SRM technology will be available from 2035 onward. Total radiative forcing of the atmosphere depends linearly on the total amount of geoengineering deployed by a coefficient ϕ_{SRM} that can assume values from -0.5 (Crutzen 2006) up to -2.5 (Rasch et al. 2008) $\frac{W}{m^2 TgS}$, and we chose an intermediate value of -1.75. The cost of implementation C_n^{SRM} are quadratic of the form

$$C_n^{SRM} = \frac{\kappa_{SRM}}{1000 * \zeta_{SRM}} * SRM_n(t)^2$$

where the SRM residence in atmosphere is given by $\zeta_{SRM} = 2$. The value of the coefficient κ_{SRM}, the cost in billion US\$ per TgS, can range from 5 (Robock et al. 2009) to 25 (Crutzen 2006) billion US\$ per TgS, and we chose an intermediate value of 10 $\$/TgS$. For the direct damages or side effects induced by SRM, given the unavailability of estimated or elicited values, take the values considered in Goes et al. (2011), who suggest economic impacts of a fixed percentage of GDP for a given amount of SRM (3% for 3.5 $\frac{W}{m^2}$ of radiative forcing). Moreover, we implement a quadratic specification:

$$\Omega_n^{SRM} = \delta_{SRM} * \left(\frac{-\phi_{SRM} * \sum_i SRM_n(t)}{3.5} \right)^2$$

And since there is substantial uncertainty about SRM collateral damages, we let the δ_{SRM} coefficient range from 0.01 up to 0.03 (original specification) and perform a sensitivity analysis. The full model description is available at Gazzotti et al. (2021).

4 Results

In this section, we focus on the case where we applied the γ-core stability concept in absolute majority power threshold ($\theta_{SRM} = 50\%$) scenario and relegate the other cases to the Appendix. Specifically, the internal stability is explored in Appendix (A), and a different power threshold is explored in Appendix (B). We will often include the grand coalition in the plots, even though it is not a stable coalition, to allow comparison with the global socially optimal deployment. Moreover, some figures will contain the results of SRM development in a free-driver non-cooperative scenario, with a single deployer. Even though we do not believe it to be a realistic scenario, these results are included in our plots to put our work into perspective with the existing SRM literature.

We find that the availability of SRM increases the number of coalitions that are internally or γ-core stable: benefits brought by geoengineering partly offset the costs of free riding and thus of cooperation, therefore improving stability in general. We find this result to be consistent for different values of the power threshold θ_{SRM} and damage factors of SRM δ_{SRM} (see Table 2).

Notice that the number of stable coalitions is not linear with the increase of the damage factor δ_{SRM} but is instead U-shaped. To explain this, we need to explore the percentage of

Table 2 Number of stable coalitions in various scenarios

	Without SRM	SRM = 1%	SRM = 2%	SRM = 3%
γ-Core stable coalitions $\theta_{SRM} = 50\%$	1 (0.05%)	652 (35.19%)	493 (26.61%)	666 (35.94%)
γ-Core stable coalitions $\theta_{SRM} = 33\%$	17 X(1.12%)	774 (51.06%)	585 (38.59%)	615 (40.57%)
Internally stable coalitions $\theta_{SRM} = 50\%$	0 (0%)	229 (12.36%)	94 (5.07%)	91 (4.91%)

rejection for each region when asked to join a coalition, depicted in Fig. 1. When SRM is allowed, we find that three regions become pivotal for stability due to their mitigation potential and geographical location and climate: Canada, Russia, and China. We find two opposing trends, the combination of which generates the peculiar U-shape: Canada's rejection rate decreases with the increase of δ_{SRM}, whereas the opposite happens for the Asian regions. The reasons why these regions reject the proposed coalition are completely different from each other: high emitters, such as China, reject a proposed coalition whenever the mitigation requests are too high, because they would need to spend a lot in abatement. Canada, on the other hand, typically rejects proposed coalitions when paired with hot countries that want to deploy high level of SRM. Rejection rate is thus inversely proportional to the amount of SRM deployed, which is generally inversely proportional to δ_{SRM}, as shown in Figure 2. High levels of geoengineering are indeed unfavorable to a cold region such as Canada, which risks becoming even colder, whereas is attractive for China, which can substitute emission reduction policies and thus reduce total mitigation costs. Also note that we are only considering a static coalition formation game, meaning that agents simultaneously form

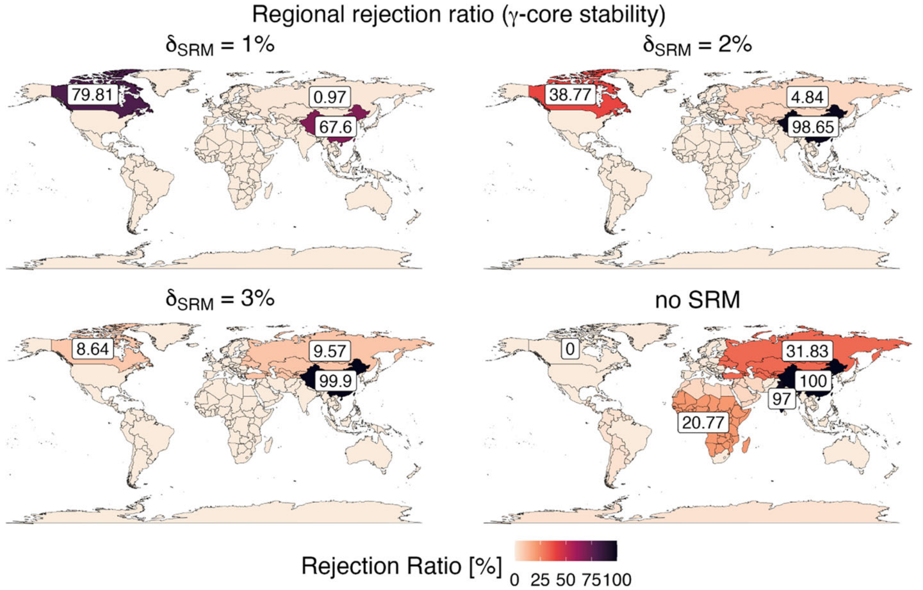


Fig. 1 Regional rejection to proposed coalitions, expressed as $\frac{\text{rejected coalitions}}{\text{coalitions that include the region}}$. Various maps show the effect of geoengineering damage sensitivity

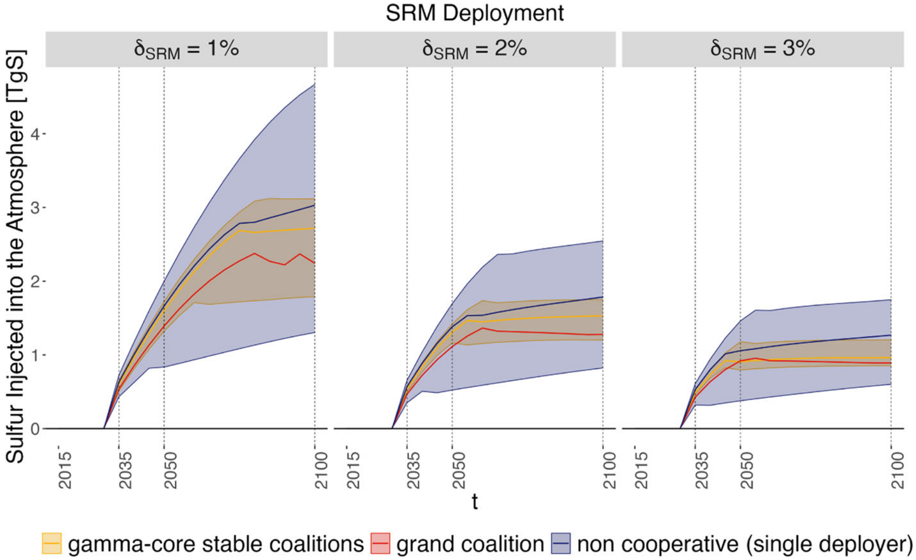


Fig. 2 SRM implementation over time in various damage scenarios. Ranges show the 5th–95th quantile distributions

coalitions without any sequential or temporal considerations. After an initial coalition is proposed and rejected, no other coalitions will be formed. If this was not the case, we could imagine a complex process in a dynamic game, wherein players carefully weigh the option of departing from a coalition for individual gains, recognizing the potential formation of an alternative coalition that yields inferior outcomes. In a similar scenario, Canada could remain in a coalition which is statically unstable just to avoid the formation of a coalition composed by hotter regions that would implement massive amounts of SRM, which is not beneficial for the North American region. A similar experiment, although interesting, requires however an incredible computational effort and would be impossible to perform at the scale and level of detail at which we operate (17 regions and a full Nash equilibrium IAM simulation). We must add a quick comment about other big regions such as the USA and India that, in our closed membership thermostate game, are not influential for the stability of coalitions. This is due to the combination of countries power weights, which affect the structure of MWCs. In the future, the weights of countries might be different due to different growth patterns, and we could have India catching up and Russia being no longer pivotal player.

In Fig. 2, we compare SRM deployment in various coalitions scenarios, ranging on collateral damage levels δ_{SRM}. In a non-cooperative scenario with the absence of a power requirement for SRM implementation, there is a great variability in deployment, depending on the region that is allowed to perform geoengineering. In the traditional literature of free-driving, this would result in the region with the most incentives to perform by themselves extreme levels of SRM. In cooperation scenarios, there is much less variability instead, and lower overall levels of geoengineering are deployed. Moreover, in non-cooperative scenario, after quickly reaching a regime value, SRM slowly increases over time to compensate the lack of mitigation, whereas it maintains constant when members of a coalition are cooperating, and it even decreases over time when it is controlled by the grand coalition. The combination of these factors further motivates our rejection of the possibility of SRM being implemented unilaterally in an uncontrolled manner.

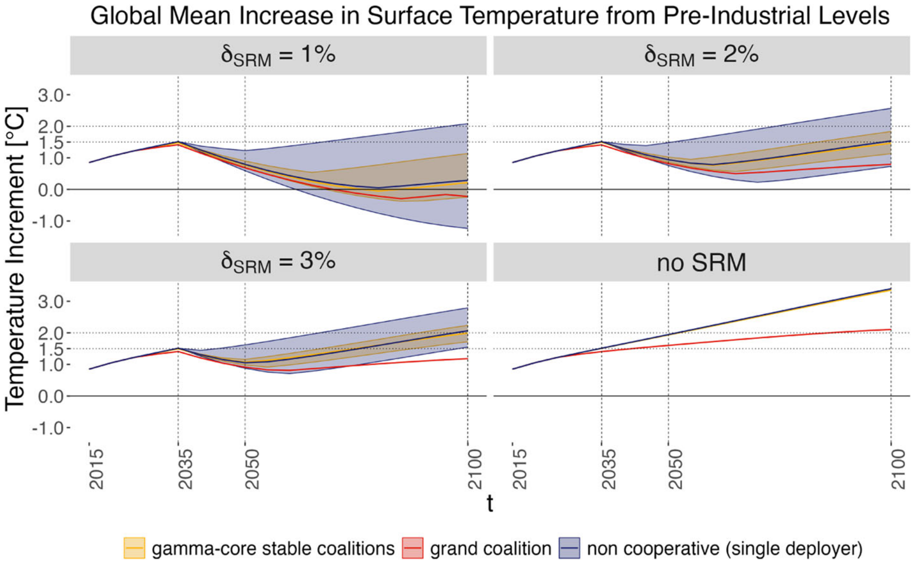


Fig. 3 Temperature evolution in various damage scenarios. Ranges show the 5th–95th quantile distribution

As seen in the “Introduction”, it is crucial not to stop the analysis at stability but to also consider the amount of climate change prevention that stable coalitions can achieve, since there is often a trade-off between the two factors.

We find that coalitions are not only stable but also effective: Fig. 3 shows the evolution of the global mean increase in surface temperature in the various scenarios. The variability we see in the results is, as before, strictly related to the variance of the SRM deployment in the various cooperation scenarios. The stable SRM coalitions manage to stay below 2° in 2100, a temperature that, without geoengineering, could only be reached by the grand coalition. The coalition that was stable also without SRM was as ineffective at preventing climate change as the non-cooperative singletons, surpassing 3° of warming.

In Fig. 4, we highlight a typical literature result: even though some non-cooperative scenarios with a free driving agent we reach low temperatures, it is only thanks to higher than socially optimal levels of SRM, that cause high collateral damages. This is one of the main concern when the topic is brought up in discussions. Here, we show that coalitions are instead much more careful in their SRM usage and behave closely to what the grand coalition would do. This further proves the point that including SRM in negotiations could be beneficial, since many fears about potential overuse of geoengineering only apply to the free-driving scenario. In Fig. 5, we show a recap of the regional differences (We further explore regional inequality via the Gini index in Fig. 6).

This is furthermore explored in Fig. 7 that compares the temperature reduction in 2100 (from business as usual scenario, where no action is taken to prevent climate change) caused by SRM with the one obtained by mitigation. We find that geoengineering can help reach the Paris Agreement, both thanks to a direct temperature reduction that can vary from 1 to 3.5 °C and by allowing climate coalitions to become stable and reduce around 0.5 °C through cooperative mitigation. This partial cooperation improves the non-cooperative optimum, but still is far from the global social optimum which reduces almost 1.5 °C through mitigation alone. We find moreover a peculiar cluster structure, highlighted in Fig. 8: coalitions that

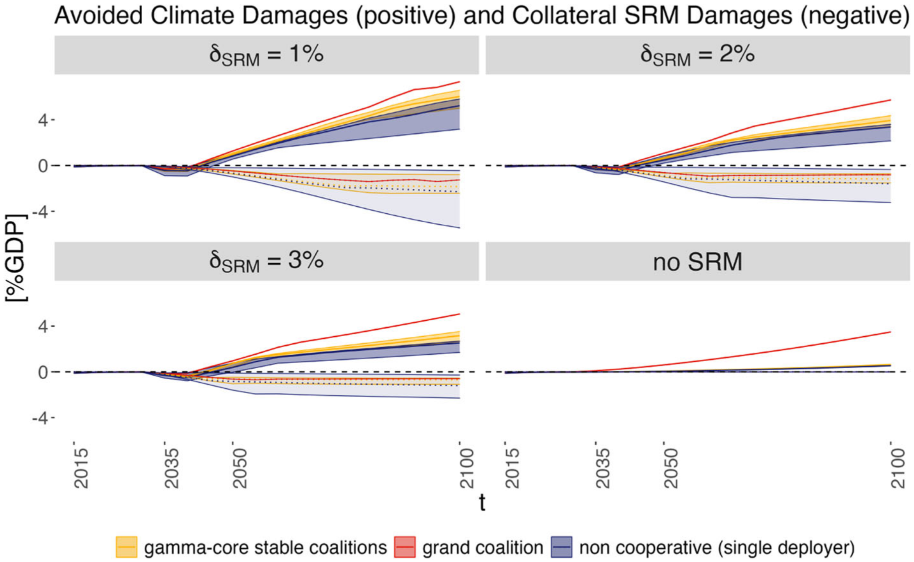


Fig. 4 Evolution of avoided climate damages (positive, darker color) against collateral SRM damages (negative, lighter color) in the stable coalitions found. Ranges show 5th–95th quantile distribution

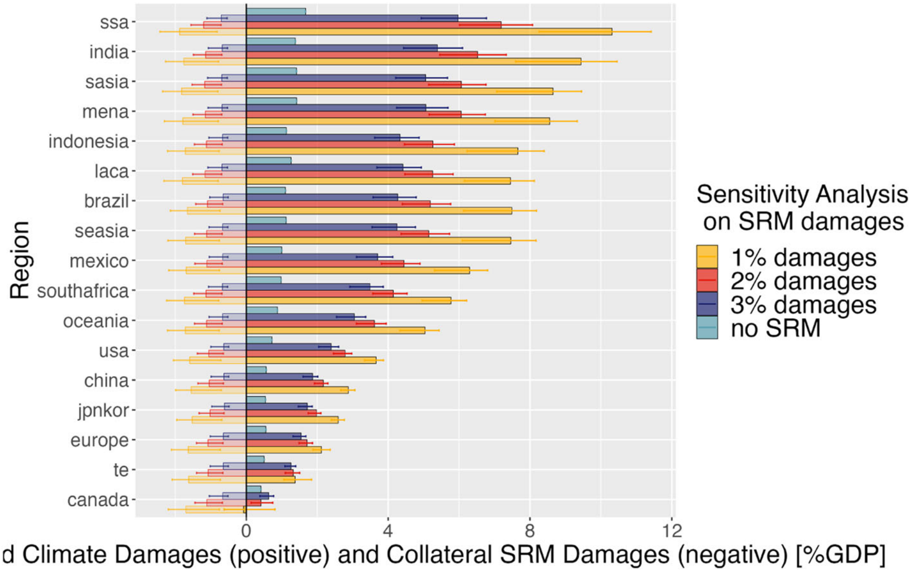


Fig. 5 Distributions of regional avoided climate damages (positive, darker color) against collateral SRM damages (negative, lighter color) in the γ-core stable coalitions found. Error bars range from 5th to 95th quantile, and we show the effect of geoengineering damage sensitivity

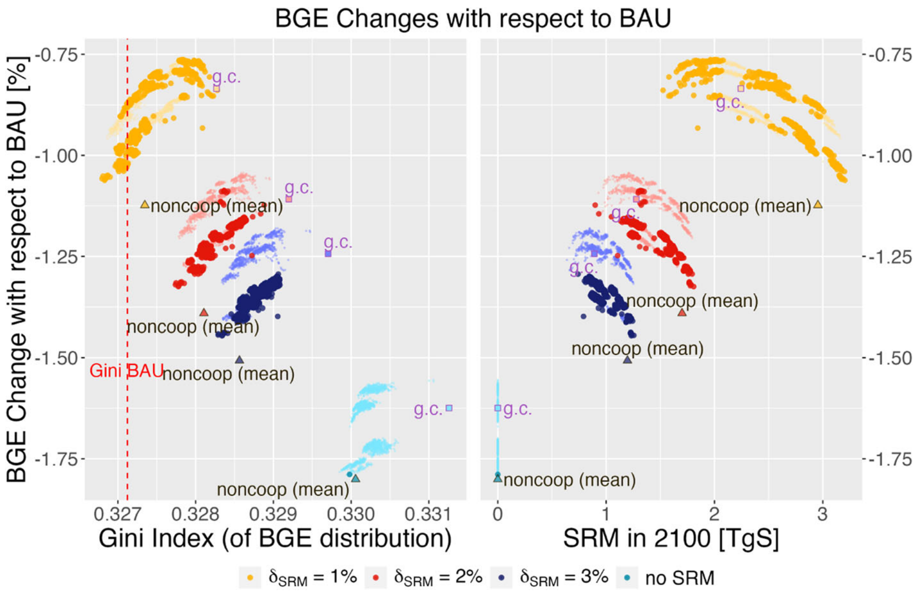


Fig. 6 Comparison of BGE change (with respect to BAU) against GINI index of GDP and SRM deployment in 2100. Darker circles each represent a solution with a γ-core stable coalition, whereas unstable ones are visible in a lighter color. We plot also the mean non-cooperative solution and the grand coalition. The effect of geoengineering damage sensitivity is shown

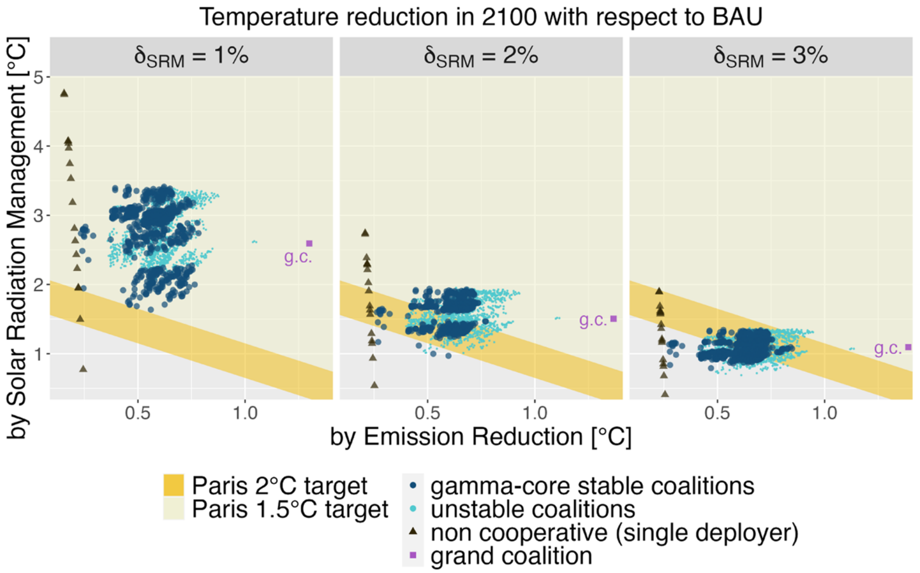


Fig. 7 Comparison of °C of temperature reduced (with respect to BAU) in 2100 by emission reduction policies against SRM effects. These are computed comparing SRM simulations results with an approximation of the temperatures that would be obtained with the same abatement policies, computed via a simplified carbon budget equation. Darker circles each represent a solution with a stable coalition, whereas unstable ones are visible in a lighter color. Triangles are all the non-cooperative solutions with a variable single SRM deploying region, and the purple square is the grand coalition solution. Background colors serve as a reference for Paris Agreements targets. The effect of geoengineering damage sensitivity is shown

include Canada use considerably less geoengineering than the others, but when SRM damages are high, some of them fail to keep global warming below 2°.

5 Conclusion

We study the interaction between mitigation and geoengineering climate policies, which have been gaining attention in recent years due to the lack of progress in global mitigation efforts. Recent studies have been highlighting how SRM is more a political or governance matter than a technical one. Therefore, the necessity of a strategic analysis is at the core of our contribution. We extend the Integrated Assessment Model RICE50+ to provide a real-world quantification and confirmation of the analytical results found in the literature. We analyze an exclusive membership coalition process where coalitions decide geoengineering deployment and mitigation jointly. We solve a two-stage game of coalition formation backwards induction and then check the stability of the coalitions and their effectiveness. We find that SRM is likely to enhance coalition stability: benefits due to geoengineering partly offset the costs of cooperation due to the free-riding incentive, improving stability of climate coalitions in general. We find stable coalitions to be effective, partially overcoming the trade-off between mitigation and geoengineering, with most of them able to reach Paris Agreement targets. Nonetheless, the largest part of the global temperature reduction comes from the deployment of SRM itself rather than from the strengthened mitigation resulting from coalition formation. This reduces the potential value of SRM for climate cooperation given the potentially high SRM risks and the uncertainty around them. Nonetheless, our results suggest that embedding geoengineering in international climate negotiations could be beneficial to avoid worse outcomes of excessive heat due to lack of both mitigation and SRM or excessive cooling due to too high levels of geoengineering.

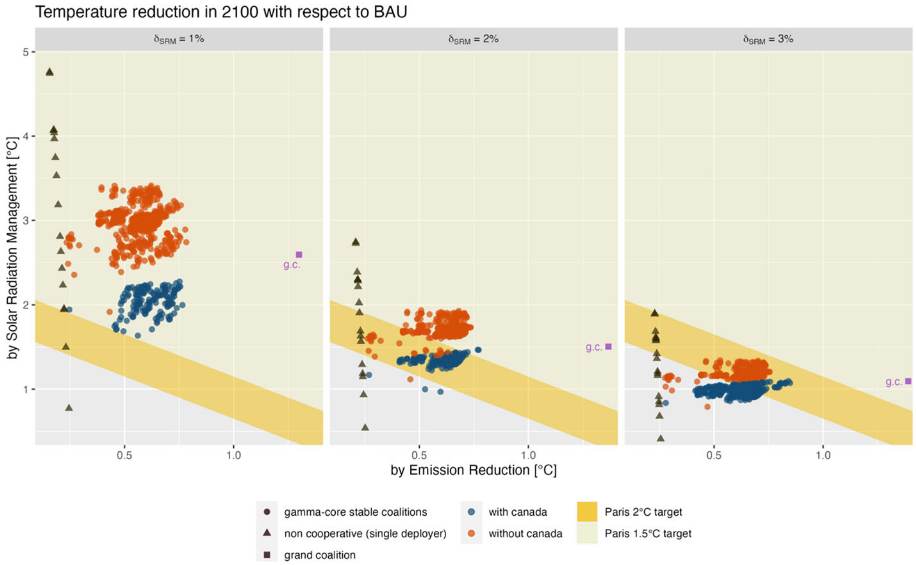


Fig. 8 Same plot as Fig. 7, but now circles are colored differently if the stable coalition contains Canada or not in order to highlight two separate clusters

Appendix A. Results for internal stability

In this section, we present the graphs for the simulations where instead of γ-core stability internal stability was considered.

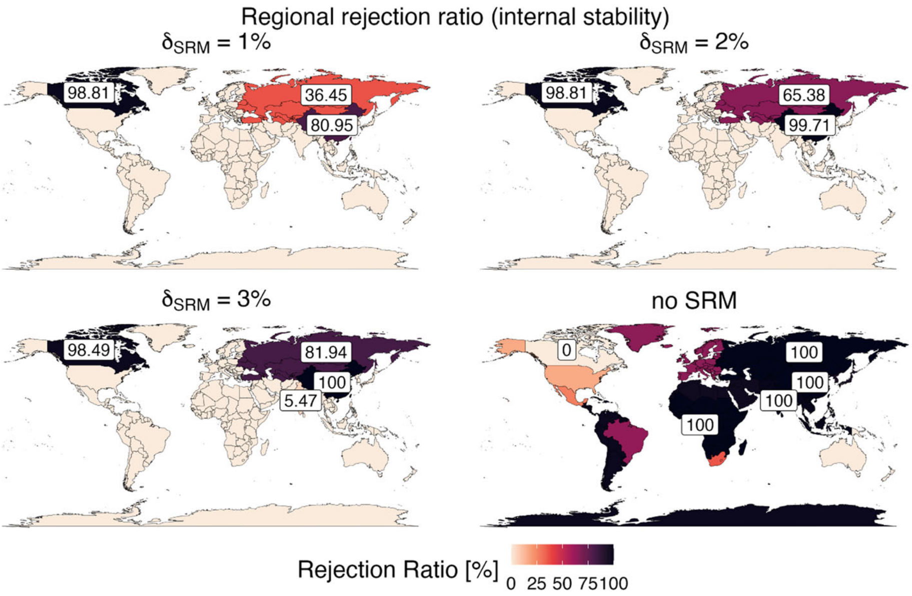


Fig. 9 Same as Fig. 1

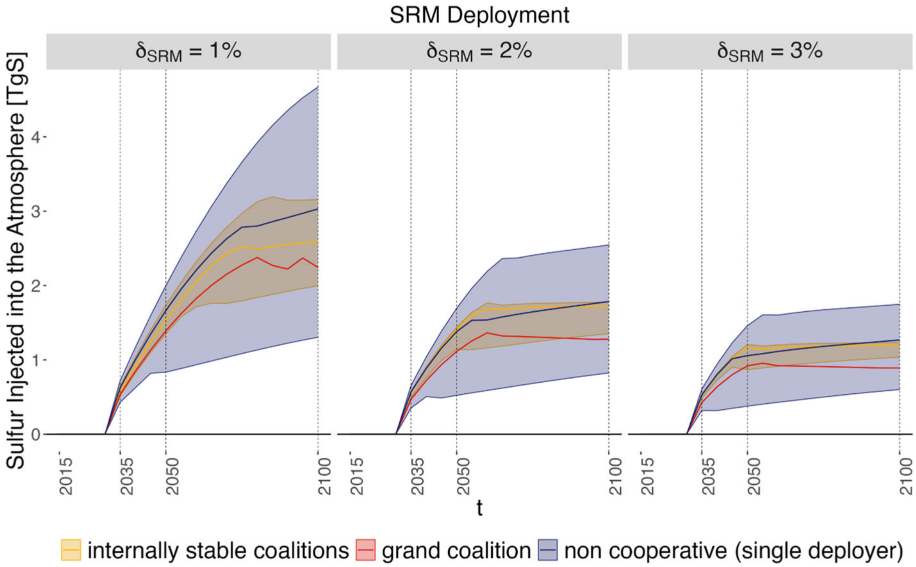


Fig. 10 Same as Fig. 2

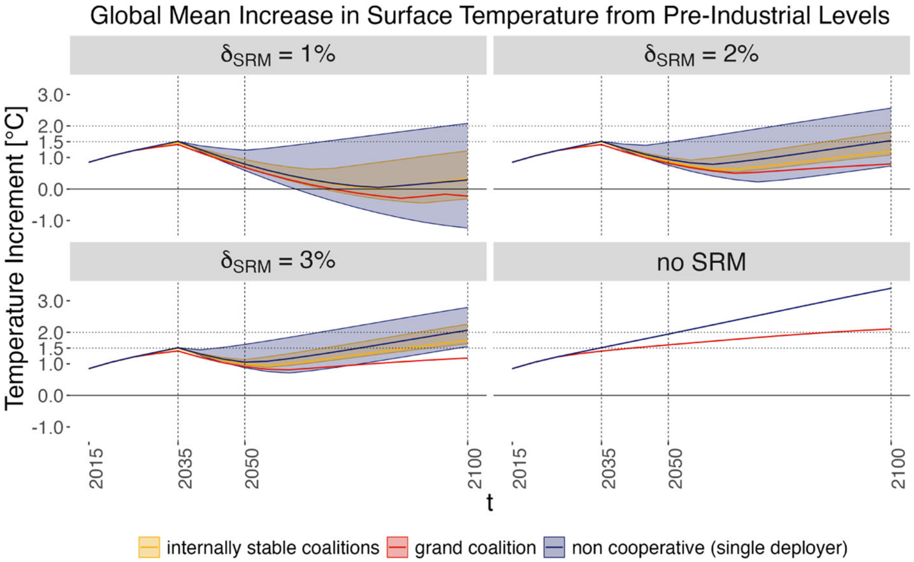


Fig. 11 Same as Fig. 3

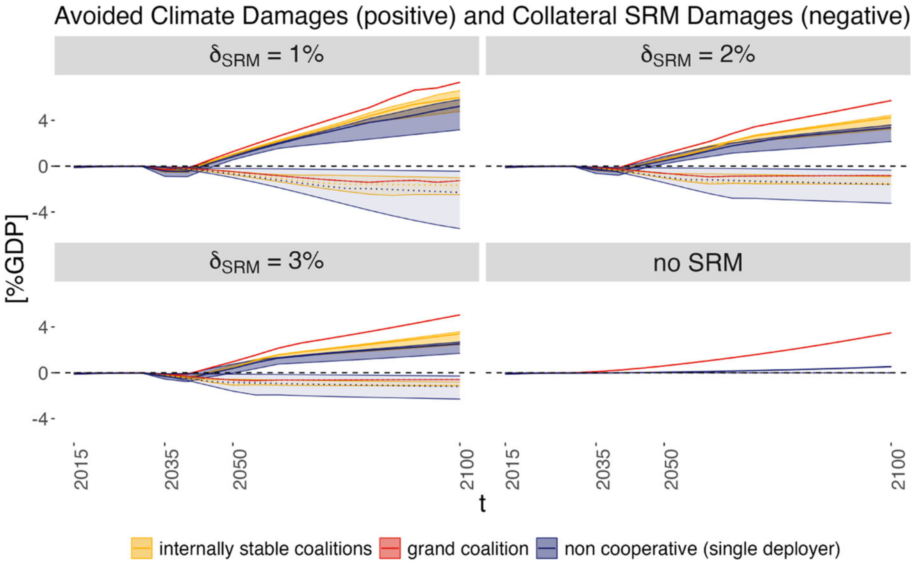


Fig. 12 Same as Fig. 4

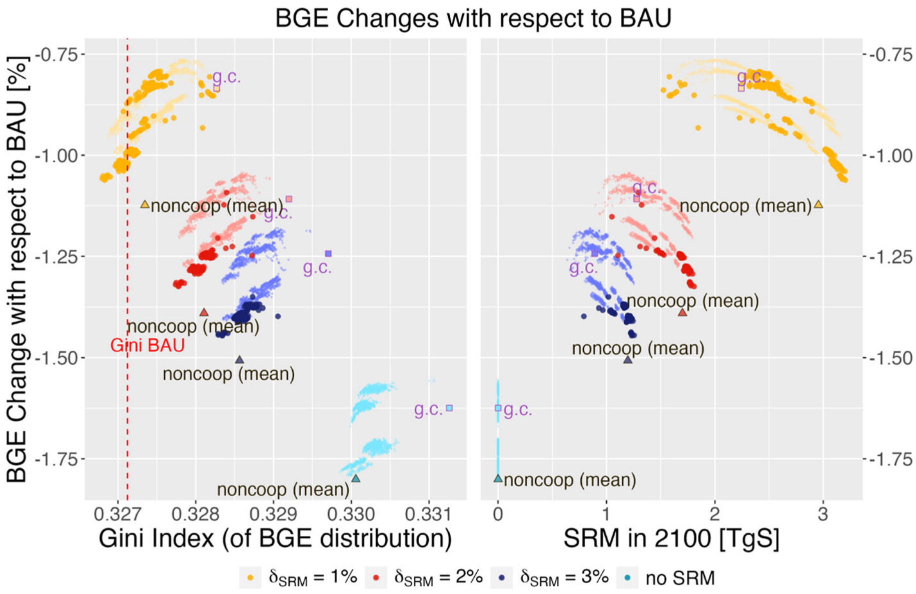


Fig. 13 Same as Fig. 6

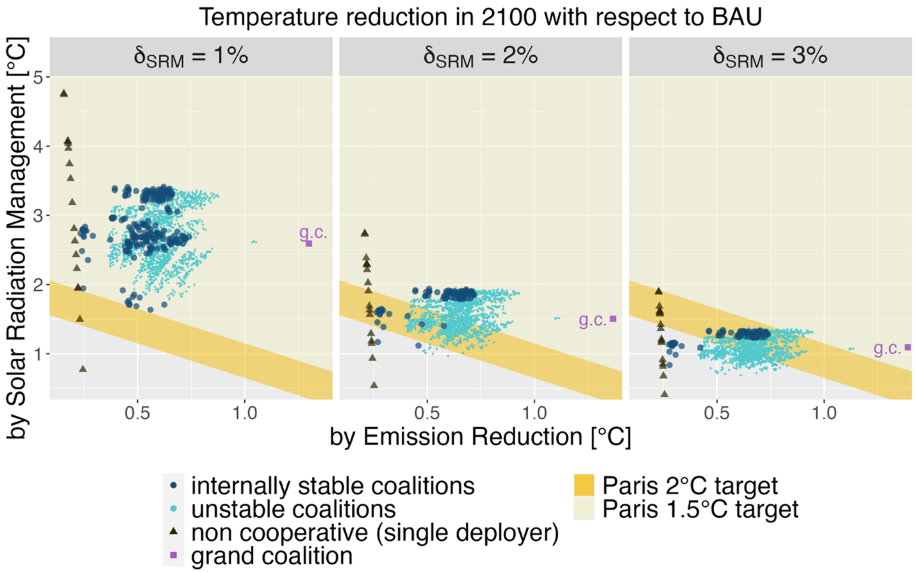


Fig. 14 Same as Fig. 7

Appendix B. Results for γ-core stability with a power threshold of 33 %

In this section, we present the graphs for the simulations that used $\theta_{SRM} = 33\%$.

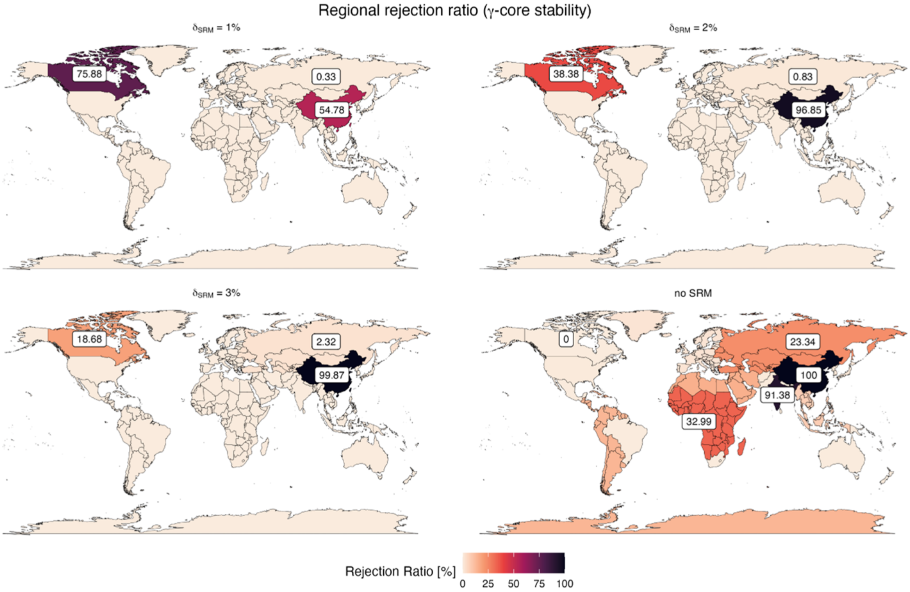


Fig. 15 Same as Fig. 1

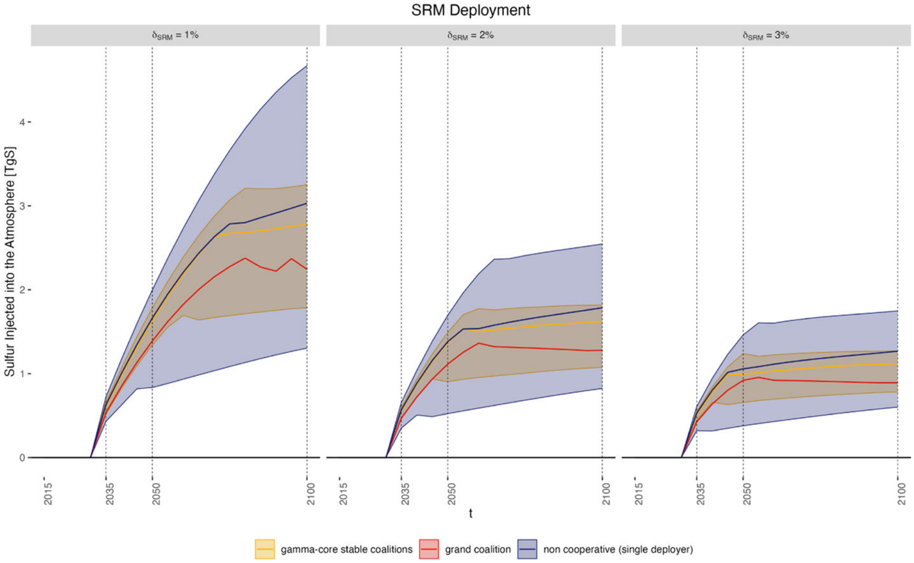


Fig. 16 Same as Fig. 2

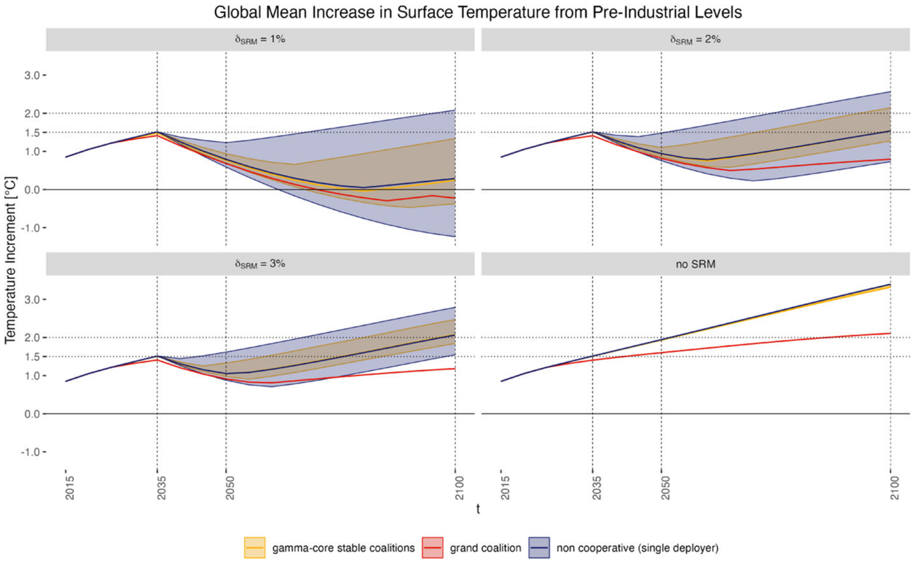


Fig. 17 Same as Fig. 3

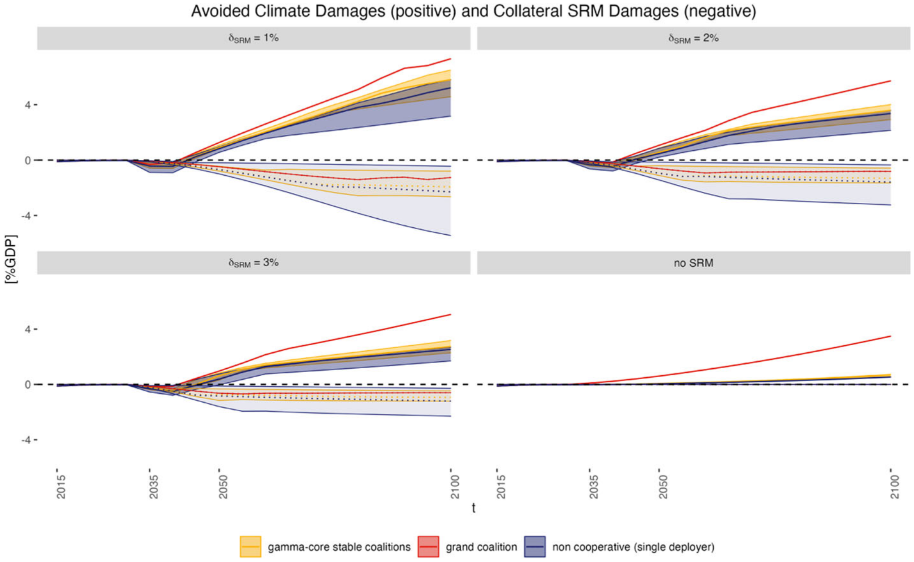


Fig. 18 Same as Fig. 4

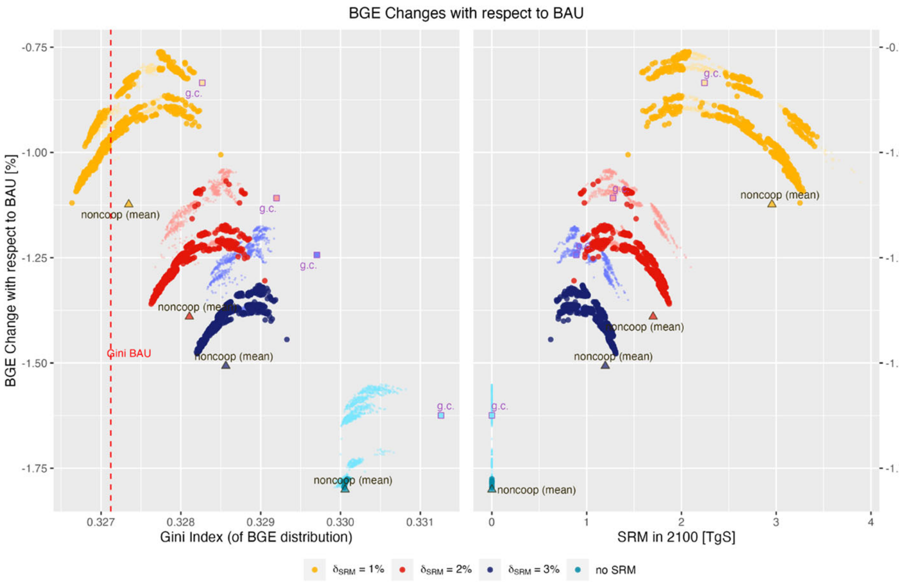


Fig. 19 Same as Fig. 6

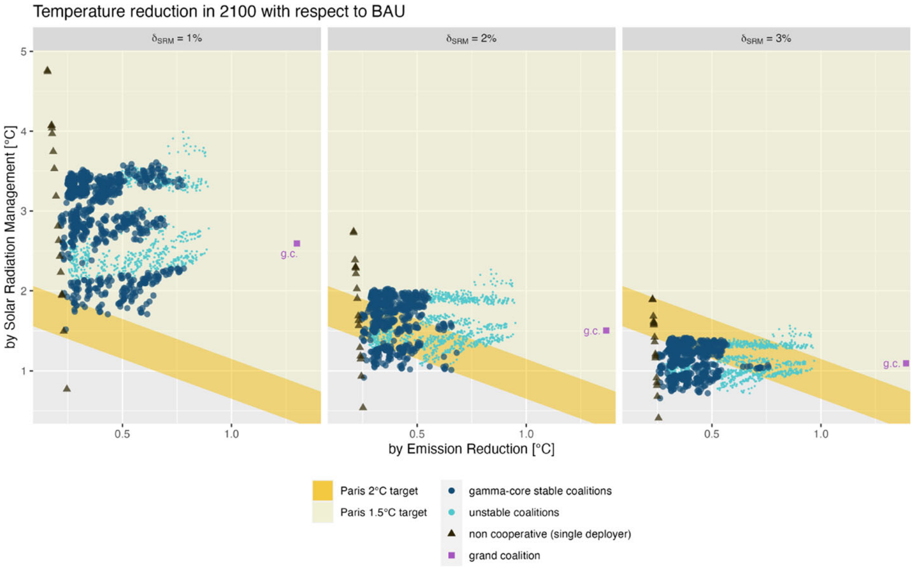


Fig. 20 Same as Fig. 7

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Data Availability The main model and SRM module are open-source available at https://github.com/witch-team/RICE50xmodel.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical standard The authors have no financial or proprietary interests in any material discussed in this article.

Informed consent Neither human participants nor animals were involved in this research.

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