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PERSPECTIVE

Stabilizing time-lagged climate impacts requires net-negative emissions for centuries

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1. Introduction

On 23 July 2025, in response to a 2023 request from the United Nations General Assembly [1], the International Court of Justice (ICJ) issued its seminal advisory opinion on the obligations of states in respect of climate change [2]. The ICJ was of the unanimous opinion that climate treaties impose binding obligations on States to protect the climate system and wider environment from human-induced greenhouse gas emissions, and that under customary international law they must exercise due diligence and use all means at their disposal to prevent activities within their jurisdiction or control causing significant harm to either ([2], para 457).

This perspective examines the implications of the ICJ's Opinion for addressing time-lagged impacts (TLIs), specifically sea-level rise above pre-industrial levels (SLR) and cumulative CO_2 emissions from permafrost thaw (PFT). We argue that SLR and PFT are clear examples of the 'significant harm' identified by the court and find that halting their growth would require net-negative emissions sustained over centuries. This frames the Paris agreement targets as ambitious milestones rather than endpoints of climate mitigation and calls for recognition of long-term international responsibilities for carbon removal—an issue that warrants urgent attention in climate negotiations.

2. The relevance of the ICJ's opinion for TLIs

While global mean temperature serves as a useful proxy for many climate-related impacts, and is commonly used in integrated assessment models (IAMs) to estimate instantaneous economic losses [3], some of the most critical climate impacts are time-lagged and continue to grow for centuries even if global temperatures stabilize at 1.5 °C [4]. Many of these impacts exhibit hysteresis or are effectively irreversible on human timescales [5]. Notable examples include large-scale ecosystem shifts [6], PFT [7], the loss of polar ice sheets, and the resulting contributions to SLR [8], as well as emerging evidence of persistent continental drying [9].

The court addressed the temporal scope of the obligation to prevent significant harm only obliquely. For instance, it opined that States 'are subject to the duty to prevent significant harm either where no harm has yet been caused but the risk of future significant harm exists, or where some harm has already been caused and there exists a risk of further significant harm ([2], para 274).' More generally, the ICJ emphasizes that '… the specific character of the risk of significant harm to the climate system is indisputably established. The best available science, as presented by the IPCC, confirms that cumulative GHG emissions are the primary source of risks arising from anthropogenic climate change' (para 137), and addresses in detail the relevant scientific background (paras 72–87).

With no doubt SLR and PFT can be attributed to GHG emissions. Their consequences for human societies and ecosystems are projected to become severe in the future and disproportionately affect vulnerable populations. Specifically, SLR poses a major threat to coastal infrastructure and the 'blue economy' [10], with damage and adaptation costs projected to reach hundreds of billions of dollars annually [11]. While globally binding limits for SLR have not been identified, hard limits to adaptation are already evident for low-lying island states facing permanent inundation. In many other regions, soft limits, such as inadequate funding, weak governance, and limited access to technology, may be hard to overcome [10, 12].

Permafrost, on the other hand, covers approximately 20%–25% of the Northern Hemisphere's land area and stores nearly twice the amount of carbon currently in the atmosphere [13]. Its thaw and the subsequent release of CO_2 and methane via enhanced microbial decomposition creates a potent carbon feedback to global warming and directly increases climate risks globally. For local communities, it further contributes to the destabilization of buildings, roads, and other infrastructure; the disruption of water systems; and increased risks of landslides and erosion [14]. It also presents a potential biohazard due to the release of long-dormant pathogens from previously frozen soils [15, 16].

Taken together, these characteristics lead us to view PFT and SLR as illustrative examples of the 'significant harm' referenced in the ICJ's opinion. Accordingly, harm prevention should be understood as requiring the stabilization of impacts at the lowest attainable level, which is not an overshoot concept: once specific impact levels have been reached, and adaptation measures such as coastal defenses or infrastructure relocation have been implemented, additional removals to reverse TLIs may yield diminishing returns. Reversal is slow or physically infeasible on human timescales, and economically unwarranted.

3. Impact stabilization at the lowest attainable level

Growth rates of PFT and SLR are complex and path-dependent functions of temperature, which remain only partially understood. For conceptual illustration, however, we invite the reader to view TLIs as inert moving objects that must be brought to a stop. The object's initial position is given by the TLI level at peak temperature, while its initial velocity corresponds to the TLI growth rate determined by that peak temperature. The rate at which this velocity can be reduced is determined by the rate of atmospheric CO_2 drawdown. The position at which the object ultimately comes to rest—the TLI stabilization level and its corresponding temperature—depends on the initial position, the initial velocity (determinded by peak temperature) and the braking force (the depth of net-negative emissions). Once the TLI stops increasing, net-negative emissions can be phased out. In reality, future dynamics depend on the full warming history, TLIs do not increase indefinitely, and even under abrupt temperature reductions, SLR and PFT respond with delays. Nevertheless, this analogy helps distinguish the TLI stabilization problem from temperature-overshoot logic, in which returning to 1.5 °C from a given peak temperature is, to a first approximation, governed by cumulative net CO_2 removals and not their rate.

To assess how the lowest attainable level of TLIs is linked to (a) the choices and constraints we face in the near-term and (b) our long-term capacity to reduce atmospheric CO_2 stocks, we develop four mitigation-scenario ensembles. Each scenario is grounded in a distinct set of plausible technological assumptions which determine peak warming as well as the depth of net-negative emissions thereafter.

The technological or deployment constraints result from currently observed and emerging implementation delays (see SM methods and table S1). In addition to the Full Portfolio (FullP) scenario, which includes the unconstrained suite of technological options typically modeled in detailed process-based (dp-) IAMs [3, 17], we explore three scenarios with potential mitigation shortfalls: the final energy reduction failure (FERF) scenario reflects slower near-term emission reductions (ERs). The storage and removal constrained (StoRC) scenario imposes limits on both CO_2 storage expansion and the total capacity of BECCS and DACCS deployment. The multiple failures (MultiF) scenario combines both sets of limitations.

Despite the imposed constraints, all scenarios remain ambitious: they assume near-term peak of emissions, continued rapid renewable expansion, at least partial availability of all typical dp-IAM technologies, the AFOLU sector acting consistently as a carbon sink, as well as a prolonged period of net-negative emissions to reverse temperature overshoot and stabilize long-term impacts.

Technical aspects of the scenario generation are detailed in the SI. Briefly, each scenario consists of multiple emission pathways based on different technology parameter sets, and each emission pathway gives rise to a large ensemble of physical impact trajectories. Thus, each scenario embodies joint technological and physical uncertainties, represented as distributions over possible discrete states of the world. The technological detail and explicit treatment of parametric uncertainty should not be mistaken as an accurate representation of the deep uncertainties of future climate mitigation; accordingly, these scenarios are best read as plausible, exploratory, and internally consistent narratives that become inherently more speculative with increasing time horizon.

4. What the scenarios reveal

First and foremost, in all four scenarios, net-negative emissions must be sustained far beyond the 23rd century—even under optimistic assumptions (figure 1(a)). However, within each scenario, the range of phase-out dates spans at least two centuries, reflecting the deep joint physical and technological uncertainties underlying the duration of the impact stabilization process (figure 1(b)).

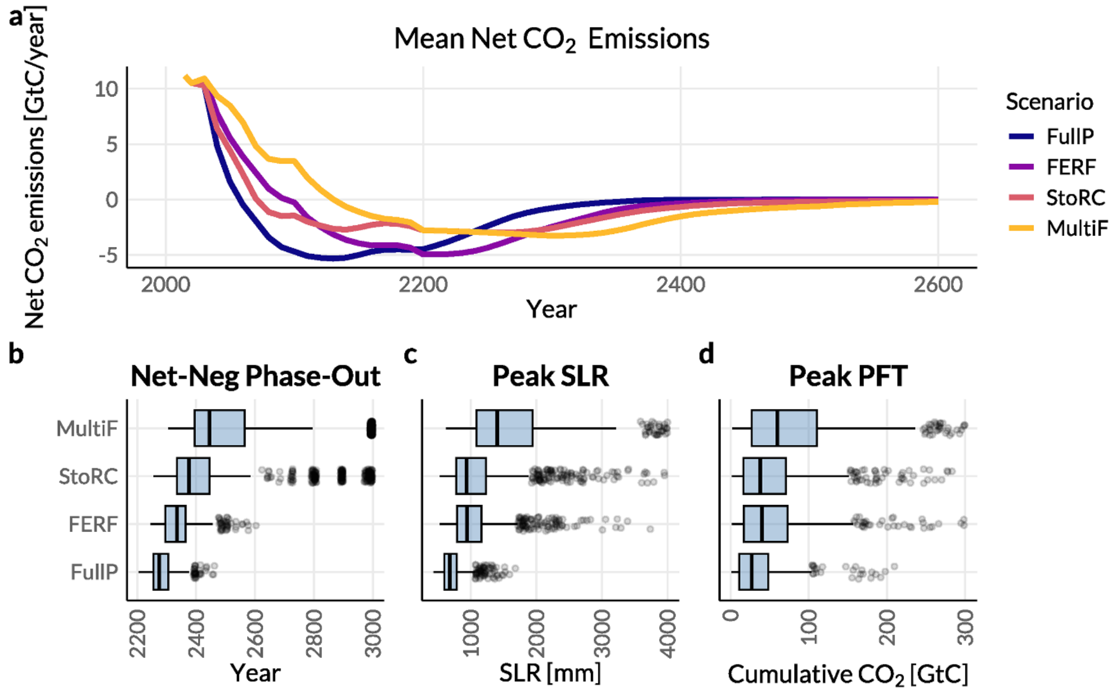

Figure 1. Comparison of four idealized mitigation scenarios and their implications for long-term net-negative CO_2 emissions and time-lagged impacts, specifically global mean sea level rise (SLR) and cumulative CO_2 emissions from permafrost thaw (PFT). For a detailed description of the scenarios, see table S1 and the Methods. Panel a shows the mean annual net CO_2 emission pathways for each scenario. Panel b displays the distribution of net-negative emissions phase-out dates, defined as the earliest point at which both impacts stop increasing. Panels c and d show the distributions of peak SLR and peak cumulative CO_2 emissions from PFT, respectively. Note, in panel c, 0.3% and 4.4% of data points are larger than 4000 mm in the StoRC and MultiF scenarios, respectively. In panel d, 0.1%, 0.4% and 2.4% of data points are larger than 300 GtC in the FERF, StoRC and MultiF scenarios, respectively. All distributions are illustrated as box-and-whisker plots, where the box represents the interquartile range (25th–75th percentile), the central line indicates the median, and the whiskers extend to the most extreme values within 1.5 times the interquartile range.

Second, the long-term temperature associated with impact stabilization is not a constant; it is endogenously determined by scenario characteristics. In our Paris-consistent scenario, FullP, the median peak temperature is around 1.7 °C and net-negative emissions are substantial (∼5 GtC/year), so the impact-stabilizing temperature is near pre-industrial levels, slightly below 0.5 °C (see figure 2). Consistent with this, TLI levels are the lowest among all scenarios (figures 1(c) and (d)). By contrast, in the least optimistic scenario, MultiF, the peak temperature is around 2.5 °C, net-negative emissions are more limited (∼2.5 GtC/year), hence, the stabilization temperature is slightly below 1.5 °C, with the highest associated impact levels.

Third, delays to earlier mitigation not only raise the median impact level, they also increase the spread of projected outcomes (figures 1(c) and (d)). Permafrost emissions are projected to account for around 5% of the cumulative net CO_2 removal burden (median). In extreme states (excluding outliers) this share remains below 15% in the FullP scenario, but moves to above 30% in the MultiF scenario (figure S8). In short, delays in mitigation do not just increase expected TLIs—they also make outcomes substantially more uncertain and thus more difficult to govern.

Finally, because ERs scale in the near term, they are more relevant for determining the peak temperature. CDR, by contrast, contributes more to post-peak temperature decline (recognizing that CDR also contributes to near-term net ERs and ERs remain important in the long run to limit residual emissions). By implication, CDR and ERs are structurally different but equally important instruments for impact stabilization. We show that one-sided policies that prioritize either ERs or CDR are likely to fall short in this context: the ER-constrained FERF scenario starts from a higher peak temperature but achieves a faster decline than the CDR-constrained StoRC scenario (figure 2), which starts from a lower peak level. Both scenarios ultimately converge to a similar stabilization temperature (just below 1 °C) and similar impact levels above the FullP scenario.

5. Harm prevention could imply removal obligations

The ICJ notes that the ultimate objective of the UNFCCC is to achieve ‘stabilization of greenhouse gas concentrations in the atmosphere at a level that

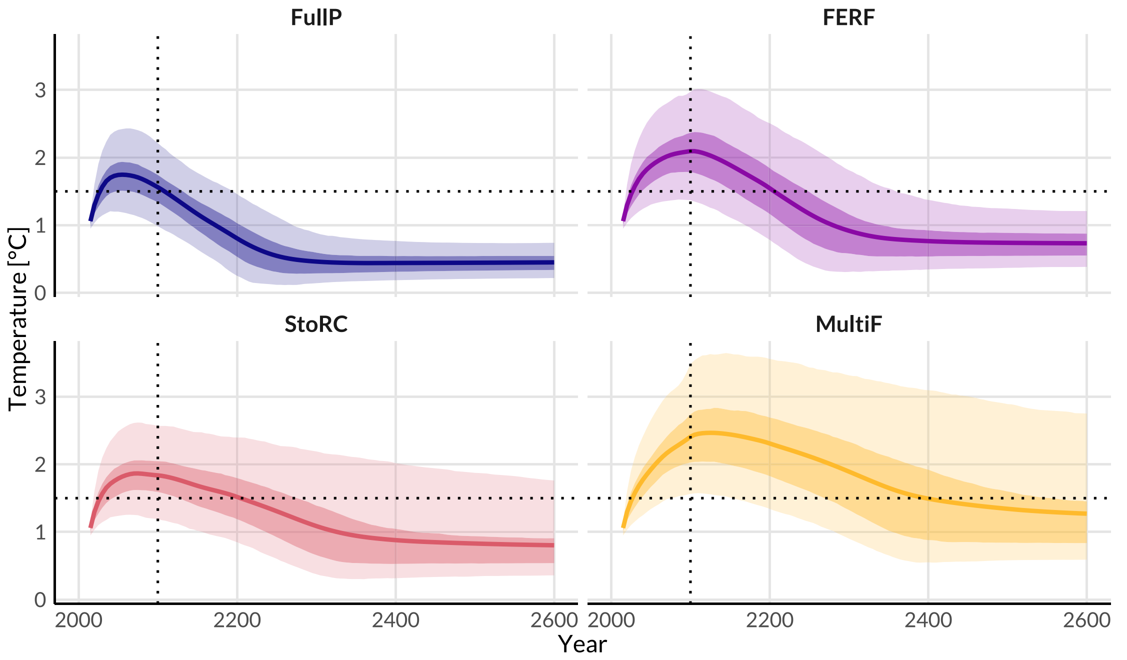

Figure 2. Global mean surface temperature increase above pre-industrial levels for each scenario. Shaded bands indicate uncertainty ranges across the ensemble: the darker band shows the interquartile range (25th–75th percentile), and the lighter band shows the 5th–95th percentile range. The dotted lines mark the year 2100 and the 1.5 °C global temperature limit under the Paris Agreement. Only the FullP scenario complies with Paris Agreement targets.

would prevent dangerous anthropogenic interference with the climate system' ([2], para 197) and that mitigation lies at the heart of that objective (para 200). Further, the temperature goal in the Paris Agreement is aimed at enhancing implementation of the UNFCCC and its objective (paras 223 and 225).

Our analysis suggests that, for TLIs, the Paris targets represent necessary but not sufficient conditions—milestones but not endpoints—on the pathway to long-term impact stabilization. As in our FullP scenario, staying below 2 °C and returning to 1.5 °C by 2100, places us on a favorable trajectory toward stabilizing impacts at comparably low levels, provided net-negative emissions continue beyond the point at which 1.5 °C is re-attained. Failure to meet the Paris milestones—an increasingly likely outcome given current implementation gaps and inadequate nationally determined contributions [18]—effectively locks in larger and more uncertain TLIs.

The ICJ further found that '[I]t is necessary to take into account the risks which current activities might pose in the future, including in the long term. In any case, the degree of a given risk of harm is always an important element for the application of the due diligence standard: the higher the probability and the seriousness of possible harm, the more demanding the required standard of conduct ([2], para 275).' As such, in the terms expressed by the ICJ, it is argued that there is a plausible legal trajectory toward recognizing long-term responsibilities for sustained global net CO_2 removals in order to limit harm from time-lagged climate impacts.

In our view, the implications of the ICJ's opinion—namely the need to maintain a net-negative economy for centuries—could not be more far-reaching. Robust legal, governance, and institutional architectures to ensure the fair distribution of carbon removal obligations among nations and across generations will be essential [19, 20]. This will necessarily hinge on the operationalization of common but differentiated responsibilities and respective capabilities and underscores the need for institutions capable of persisting beyond political cycles and organizational turnover [21]. Yet such integrated frameworks have not been meaningfully addressed in climate negotiations, despite their importance to any future architecture of long-term climate responsibility.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Scenario Assumptions & Logic available at https://doi.org/10.1088/1748-9326/ae34ca/data1.

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