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Revisiting permafrost carbon feedback and economic impacts

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Abstract

Quantifying permafrost carbon feedback (PCF) is a critical step in conveying the significance of permafrost carbon emissions to decision-makers and stakeholders and achieving sustainable development goals. Simply assuming a rapid reduction in permafrost area may be an overaggressive approach. This study revisited PCF by incorporating relatively clear permafrost physics into the Dynamic Integrated model of Climate and the Economy. The results show that the total carbon released from permafrost regions in 2100 is 30.5 GtC, which is accompanied by an additional atmospheric warming of 0.038 °C, much lower than previous studies. This study provides a potential perspective to scrutinize the climate feedback and related economic impacts due to permafrost thawing. We may need to pay more attention to carbon processes during nongrowing seasons and sudden changes in permafrost.

1. Introduction

Permafrost occupies 23.9% of the Northern Hemisphere's land surface (Zhang *et al* 1999). It stores approximately half of the soil organic carbon (SOC) in the Earth's soils (Hugelius *et al* 2014, Mishra *et al* 2021). Rapid climate change at high latitudes (Post *et al* 2019) results in changes in the permafrost state (Biskaborn *et al* 2019, Nyland *et al* 2021), which may influence socioeconomic systems through carbon cycles (Hjort *et al* 2022, Streletskiy *et al* 2023). SOC which is sequestered in soil for long periods will decompose to release greenhouse gases into the atmosphere because of the permafrost thawing (Natali *et al* 2019, Hugelius *et al* 2020, Turetsky *et al* 2020, Rößger *et al* 2022). This process may amplify global warming (Schaefer *et al* 2014, Burke *et al* 2017), and the net effect of widespread permafrost thawing is likely to be positive feedback to the climate system (Schuur *et al* 2008, MacDougall *et al* 2012). Moreover, permafrost carbon feedback (PCF) has potential impacts on the social cost of carbon (SCC) and the choice of optimal emission pathway (Yumashev *et al* 2019, Dietz *et al* 2021). Therefore, quantifying PCF effects stands as a pivotal stride in highlighting the gravity of permafrost carbon emissions to decision-makers and stakeholders. It serves as a crucial linkage, enabling relevant agencies to craft economically optimal climate policy pathways and navigate toward achieving sustainable development goals.

Recent studies have incorporated PCF into Earth System Models (ESMs) (Schneider von Deimling *et al* 2012, Koven *et al* 2015, Woodard *et al* 2021) and integrated assessment models (IAMs). ESMs are scientific and comprehensive tools to capture the changes in climate and environmental conditions. But they are also complex, such as more parameter requirements. Some of the models do not consider the PCF due to their open-loop climate systems (called the non-feedback systems) (McGuire *et al* 2018, Schädel *et al* 2024). IAMs have been used to describe the interaction between economic activity, greenhouse gas emissions, and climate change to quantify PCF effects (Weyant 2017), although geophysical processes are generally simplified in IAMs. The Dynamic Integrated model of Climate and the Economy (DICE), one of the famous IAMs, is a highly influential tool for analyzing issues in climatic economics and plays a critical role in academic and policy efforts (Aldy and Stavins 2020). The DICE model is an optimization model that combines the latest economic and scientific knowledge with the ability to link to multiple economic factors, capturing the key elements of climate change economics in as simple and transparent a form as possible. Therefore, we can dynamically capture the interrelationships between permafrost degradation, carbon release, global temperature, and emission reduction policies in the future.

Previous studies used a variety of ways to incorporate PCF into the DICE model and quantify the PCF effects. González-Eguino and Neumann (2016) added the predicted CO_2 and CH_4 fluxes from permafrost thawing under the RCP2.6 (Representative Concentration Pathways) to the DICE model to estimate the additional effort required to maintain a radiating forcing of 2.6 W m^{-2} in 2100. Kessler (2017) assumed that the area of permafrost degradation was a linear function of the global temperature anomaly and predicted the amount of carbon released by permafrost decomposition through the change in the area. Kessler (2017) found that by 2175, the near-surface permafrost will completely degrade. The amount of permafrost carbon released into the atmosphere will reach 137 GtC by 2100 and add 0.64 °C to the atmospheric temperature by 2300. Wirths *et al* (2018) calibrated the relationship between global temperature anomalies and permafrost CO_2 emissions based on the additional temperature rise due to PCF in the RCP4.5 scenario that Schneider von Deimling *et al* (2012) predicted. We acknowledge that changes in permafrost area are generally slow and nonlinear (Delisle 2007, Wang *et al* 2019), and many studies have noted permafrost degradation, including deepening of the active layer and increasing permafrost temperatures. Meanwhile, permafrost degradation and greenhouse gas release are generally gradual and long-term processes that occur under a warming climate (Schuur *et al* 2015). Therefore, predicting permafrost carbon release by the changes in permafrost regions may be questionable.

The degradation of permafrost is influenced by several factors, in particular, it is very sensitive to changes in near-surface air temperature (Zhang and Stamnes 1998). Deepening active layer is generally considered an important driver in permafrost carbon cycle (Koven *et al* 2011). Active layer thickness changes strongly depend on near-surface air temperature and are mainly controlled by climate conditions in the thaw season (Anisimov *et al* 1997). The temperature change in the high latitudes of the Northern Hemisphere (NH) is approximately twice that of the global mean temperature change (Notz and Stroeve 2016, Turetsky *et al* 2019). However, near-surface air temperature increases mainly occur in cold seasons across the permafrost regions (Bintanja *et al* 2011, Cohen *et al* 2014). Thus, if the global mean annual air temperature is used directly to describe the evolution of permafrost, the scale and speed of permafrost thawing are likely to be misestimated. In addition, the density of SOC in the near-surface soils is different with depth (more than 45% of permafrost organic carbon is stored in the upper 1 m of soil) (Hugelius *et al* 2014, Mishra *et al* 2021), which means that considering the variation of active layer thickness is necessary for accurate calculation of carbon release. These issues may bring uncertainty in assessing PCF effects and should be considered in a reasonable approach.

Therefore, this study aims to (i) provide a reasonable and reduced complexity description of the permafrost degradation process based on a widely used semi-physical permafrost model and (ii) incorporate a permafrost carbon module into the DICE model to evaluate the PCF effects in the future.

2. Data and methods

2.1. Data

The permafrost map compiled by the International Permafrost Association was used to define the permafrost regions within the Northern Hemisphere. The Climate Research Unit (CRU) monthly mean near-surface air temperature (TAS) data set (Harris *et al* 2020) was used to calculate the thawing index over permafrost regions using the method by Nelson and Outcalt (1987), which has been proven to be effective (Frauenfeld *et al* 2007). The CRU dataset was produced on a 0.5° × 0.5° latitude-longitude grid over the Earth's land area except for Antarctica (CRUTS v4.06) over a long period (1901–2021). We also used the global temperature anomalies from the HadCRUT5 data set, which is on a regular 5° × 5° latitude-longitude grid since 1850 (Morice *et al* 2021), because we need to connect the global mean temperature changes in the DICE model to the PCF module (see details in section 2.2.1). Considering the better quality of observations, we used these datasets during the last 50 years (1971–2020).

2.2. Methods

DICE model projects future climate and economic trajectories by factoring in growth linked to population and productivity, in conjunction with climate policies (Nordhaus 2014). The escalation of carbon dioxide emissions from industrial activities, land use changes, and other greenhouse gases amplify atmospheric radiative forcing, leading to a global

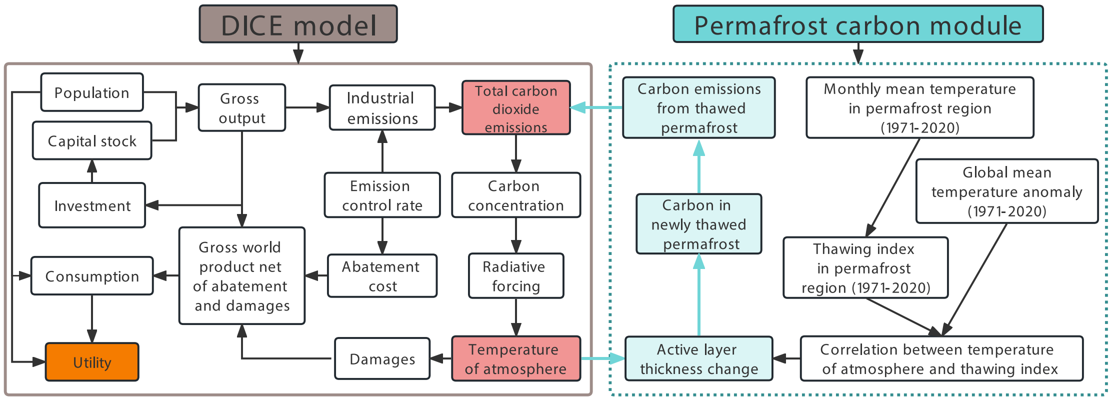

Figure 1. Schematic diagram of the coupling between the DICE model and permafrost carbon module.

temperature surge. This temperature rise poses consequential threats to the global economy and societal well-being. A notable concern is the potential contribution of carbon released from thawing permafrost to atmospheric carbon levels. As permafrost thaws, it may release stored carbon, augmenting atmospheric carbon levels and further impacting global climate dynamics.

To consider PCF, we incorporated a permafrost carbon module based on a semi-physical permafrost model into the DICE-2016R3 model. This new module needed to be a reduced complexity module able to depict the key physics of permafrost dynamics. The basic assumption is that the active layer thickness will increase with air temperature. The newly thawed zone is the main carbon source from permafrost to the atmosphere (figure 1). We assess PCF and economic impacts under two main scenarios of the DICE model, the baseline and optimal scenarios. The baseline scenario is smaller than the values of RCP8.5 but larger than the values of RCP6.0 (Nordhaus 2018b), which can help us project the levels and growth of economic and environmental variables under business as usual. The optimal scenario is a counterfactual case, which can help us estimate the cost and benefits of optimum policies.

2.2.1. Estimate active layer thickness changes

To bridge permafrost dynamics to the DICE model, we assume that the relationship between the thawing index and global temperature anomaly in permafrost regions remain stable, which ensures us predict the changes in the active layer thickness caused by future global air temperature change. First, we calculated the thawing index in the permafrost regions based on the method used by Nelson and Outcalt (1987) in permafrost prediction, which assumes the annual cycle of air temperature as an ideal sine curve, thus allowing us to use monthly temperatures in the hottest and coldest months to estimate the thawing index. Then, we established a correlation between the global temperature anomaly and the regional mean thawing index over the permafrost regions in the NH (figure 2). The estimated correlation is:

$$\mathrm{DDT_{PF}}(t) = 200.46 \times \mathrm{TATM}(t) + 1038.89 \qquad (1)$$

where TATM(t) is the global temperature anomaly (°C) at period t in the model. $\mathrm{DDT_{PF}}(t)$ is the corresponding thawing index (°C-day) over the entire permafrost regions in the NH at period t; t displays the number of period (period length is 5 years), which is consistent with the DICE model.

Second, we calculated the active layer thickness by $\mathrm{DDT_{PF}}(t)$. Stefan's method is a widely used and scientifically proven method for estimating the active layer thickness in permafrost regions (Nelson *et al* 1997, Zhang *et al* 2005). Therefore, we used the simplified Stefan formulation to calculate the active layer thickness:

$$\mathrm{ALT_{PF}}(t) = E \times \sqrt{\mathrm{DDT_{PF}}(t)} \qquad (2)$$

where $\mathrm{ALT_{PF}}(t)$ is the regional mean active layer thickness (m) over the permafrost regions at period t. The edaphic factor 'E' is a catchall scaling parameter with dimensions $(\mathrm{m}^2\ (°\mathrm{C{\cdot}d})^{-1})^{1/2}$ that blends soil thermal conductivity, density, moisture content, etc (Hinkel and Nelson 2003, Zhang *et al* 2005). The value of 'E' for each land cover class over the high northern latitudes was 0.019–0.067 $(\mathrm{m}^2\ (°\mathrm{C{\cdot}d})^{-1})^{1/2}$ (Park *et al* 2016). It varies among places based on in situ observations and mostly ranges from 0.01 to 0.10 $(\mathrm{m}^2\ (°\mathrm{C{\cdot}d})^{-1})^{1/2}$ (Peng *et al* 2018). According to the permafrost active layer thickness for the Northern Hemisphere of the European Space Agency's Climate Change Initiative Permafrost data sets (Obu *et al* 2021), we calculated that the mean edaphic factor value was approximately 0.028 ± 0.003 $(\mathrm{m}^2\ (°\mathrm{C{\cdot}d})^{-1})^{1/2}$ during 1997–2019. The parameter

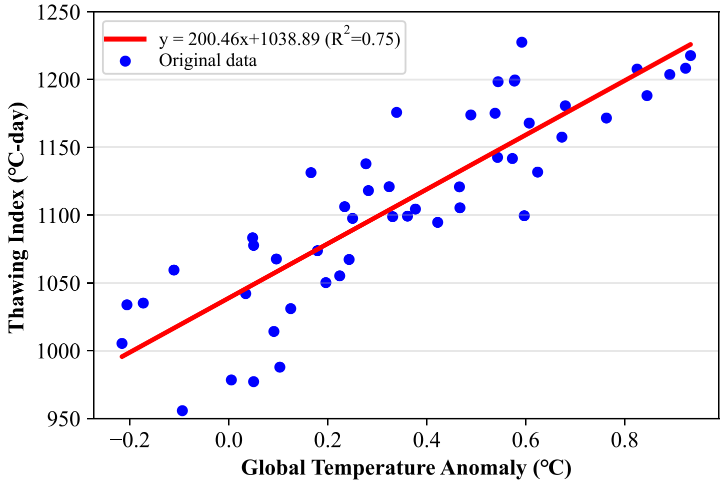

Figure 2. The fitting diagram of the linear correlation between global temperature anomaly (HadCRUT5) and regional mean thawing index over the permafrost region (CRUTS v4.06). The blue dots represent the original values and the red line is the fitted line.

'E' in the Qinghai-Tibetan Plateau could be 0.050–0.070 (m^2 $(°C{\cdot}d)^{-1})^{1/2}$ (Wu and Zhang 2010). Zhang *et al* (2005) used data from nine Russian Arctic field stations to estimate the mean value of 'E', which could be 0.045 ± 0.010 (m^2 $(°C{\cdot}d)^{-1})^{1/2}$. Considering that most permafrost carbon is stored in high-latitude permafrost, we used 0.045 (m^2 $(°C{\cdot}d)^{-1})^{1/2}$ as the base value of 'E' in our study. Meanwhile, we implemented a sensitivity analysis for 'E' ranging from 0.025 to 0.055 (m^2 $(°C{\cdot}d)^{-1})^{1/2}$.

2.2.2. Estimate the carbon amount in newly thawed permafrost

The newly increased permafrost carbon emissions were calculated by differences in the carbon in the active layer between two successive time steps:

$$C_{PF}(t) = ALT_{PF}(t) \times SOC \tag{3}$$

$$C_{thawedPF}(t) = C_{PF}(t) - C_{PF}(t-1) \tag{4}$$

where $C_{PF}(t)$ is thawed carbon in the active layer at period t; SOC is organic carbon storage in soil layers; and $C_{thawedPF}(t)$ is the amount of carbon in newly thawed permafrost at period t (GtC).

We focused on the top 3 m carbon pool because the regional mean active layer thickness is generally expected to be <3 m over permafrost regions (Hinkel and Nelson 2003, Park *et al* 2016, Peng *et al* 2018). In addition to the Arctic, the Third Pole has some organic carbon reserves (approximately 33 GtC for the 0–3 m soil depths). The data in our analysis were combined from two sources: Hugelius *et al* (2014) for high latitudes and Mu *et al* (2015) for the Qinghai-Tibetan Plateau. An overall summary of permafrost regions showed that SOC storage in three different layers is 489.3 GtC in the upper 0–1 m, 365.6 GtC in l–2 m, and 212.1 GtC in 2–3 m. To avoid potential nonconvergence problems caused by the discontinuous function, we fit a quadratic nonlinear function by the corresponding relationship between $ALT_{PF}(t)$ and $C_{PF}(t)$ within three meters to calculate $C_{PF}(t)$ (figure 3).

2.2.3. Calculate the amount of CO_2 and CH_4 released

Our carbon decomposition module is taken from Kessler (2017). The thawed carbon can be divided into passive (40%) and active (60%) pools. The active pool decomposes and releases carbon dioxide (97.7%) and methane (2.3%) exponentially. The period length of the decay release is set to 70 years (Schaefer *et al* 2011)

$$CCum_{PF}(t) = \sum_{s=to}^{t} C_{thawedPF}(s) * 60\% * \left[1 - \exp\frac{(t-s)*5}{70}\right] \tag{5}$$

$$CO_{2PF}(t) = 3.666 \times (1 - 2.3\%) \times [CCum_{PF}(t) - CCum_{PF}(t-1)] \tag{6}$$

$$CH_{4PF}(t) = 1.333 \times 2.3\% \times [CCum_{PF}(t) - CCum_{PF}(t-1)] \tag{7}$$

$$CE_{PF}(t) = CO_{2PF}(t) + RE \times CH_{4PF}(t) \tag{8}$$

where $CCum_{PF}(t)$ is an accumulation of carbon emissions from thawed permafrost to the atmosphere at period t. $CO_{2PF}(t)$ and $CH_{4PF}(t)$ are the fluxes of carbon dioxide and methane at period t. $CE_{PF}(t)$ is the total fluxes of carbon dioxide equivalent at period t. RE is a scale factor of 29 (Forster *et al* 2021) to convert CH_4 emissions from permafrost to CO_2 equivalent according to radiative efficiency difference.

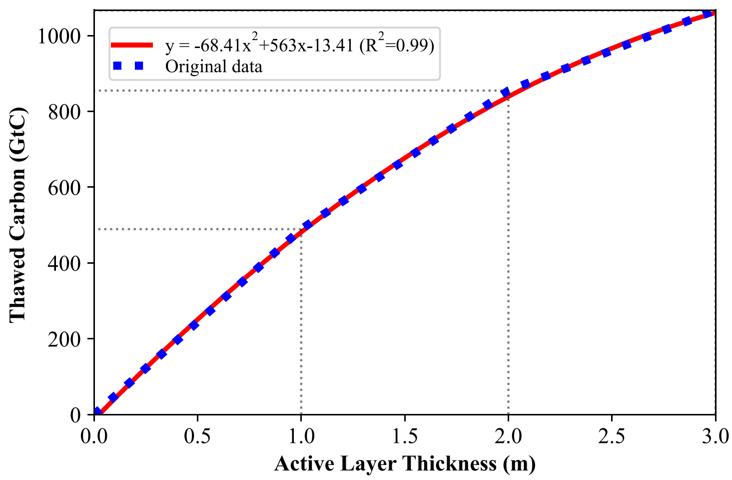

Figure 3. The fitting diagram of the nonlinear correlation between active layer thickness and thawed carbon over the permafrost region. The blue dots represent the original values and the red line is the fitted curve.

3. Results and discussion

We run the model with both baseline and optimal scenarios and then compare the results with the original results (not include permafrost carbon) to present the impacts of PCF on the global climate-economic system. Here, we focus on the 21st century, which is consistent with the targets of worldwide climate policy.

3.1. Physical impacts

To assess the model's performance, we calculated the average and standard deviation of the active layer thickness across available sites within the Circumpolar Active Layer Monitoring network, ranging from 2001 through 2015. The simulated results were derived from equation (2), utilizing an E factor of 0.045 (m^2 ($^\circ$C·d)$^{-1}$)$^{1/2}$. Overall, our approach yields the results that align closely with the observational regional averages (figure S1), showing comparable statistics (Pearson correlation is 0.66, mean bias is 0.048 m, root mean square error is 0.28 m). Admittedly, while our simplified approach sacrifices spatial diversity, it offers an acceptable approximation for the comprehensive model. Meanwhile, our projections for the active layer thickness, with an increase of about 0.4 m by 2100 compared to 2015, are close to the results of some projections of changes in active layer thickness under future climate scenarios. Peng *et al* (2018) averaged over all permafrost regions that the active layer thickness increases by about 0.22 m in total for RCP4.5 and about 0.55 m for RCP8.5 by the end of the 21st century. This partly indicated that further active layer thickness changes could be reasonable.

Carbon is constantly released from thawing permafrost, and the accumulated carbon release amounts are 2.9 GtC by 2040, 14.2 GtC by 2070, and 30.5 GtC by 2100 (figure 4(a)). The speed of carbon release in each period is different: in the early 21st century (before 2040), the average annual carbon release is only 0.12 Gt, but in the late 21st century (after 2070), it is 0.54 Gt. The permafrost carbon release rate at the end of the 21st century is faster than that at the beginning of the 21st century. This is because the decayed carbon decomposition release cycle needs a long period to release greenhouse gases into the atmosphere. Carbon dioxide released from permafrost, like carbon dioxide emitted from fossil energy consumption (industry), increases the concentration of greenhouse gases in the atmosphere and causes warming of the Earth's surface through increased radiative forcing. Consequently, the additional increase in global mean air temperature caused by the thawing permafrost is approximately 0.003 °C in 2040, 0.018 °C in 2070, and 0.038 °C by 2100 (figure 4(b)). Since the released carbon produces effects in the next period, the years 2045, 2075, and 2105 were chosen for our model, the same as below.

Our results are close to the lower bound of previous studies that used ESMs. For example, Koven *et al* (2015) predicted that permafrost thawing will release 27.9–112.6 GtC by 2100, and Burke *et al* (2017) forecasted that the PCF will bring 0.02 °C–0.11 °C additional warming in RCP8.5. Similar studies by eight models, as highlighted by Schuur *et al* (2015), indicated cumulative carbon emissions from permafrost under RCP8.5 ranging from 37 to 174 GtC (Schuur *et al* 2015). Schneider von Deimling *et al* (2015) forecasted that thawing permafrost will release approximately 60–198 GtC (methane converted to carbon dioxide equivalent) and result in 0.05 °C–0.14 °C additional warming under RCP8.5. Notably, disparities in previous studies can be attributed partly to the discrepancy in emission scenarios used, where some studies rely on the more aggressive RCP8.5

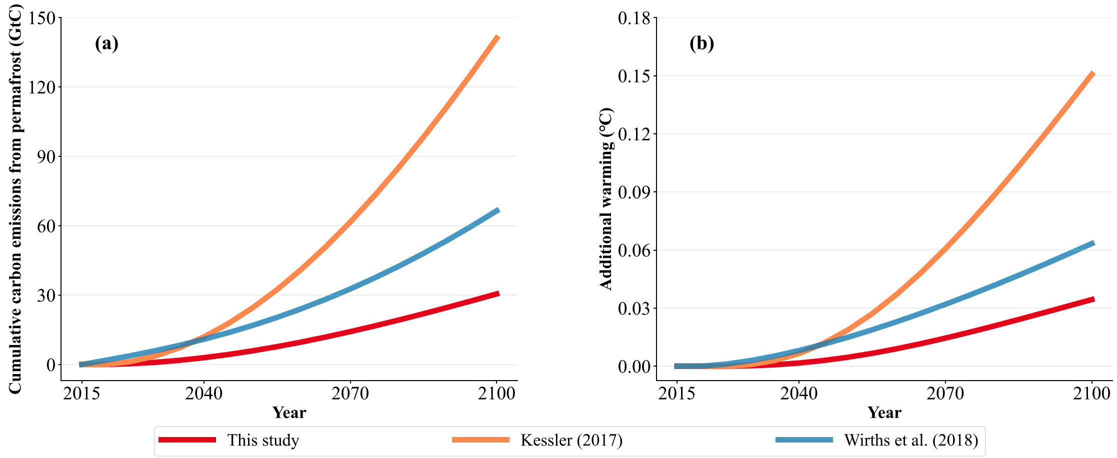

Figure 4. Projected PCF intensity in the 21st century under the baseline scenario by our method (red), Kessler's method (orange), and the method of Wirths *et al* (2018) (cyan). (a) Cumulative carbon emissions from permafrost. (b) Additional warming, which represents the difference in global temperature anomaly projections between our model considering permafrost carbon and the original DICE model.

compared to the framework within the DICE model (Nordhaus 2018a). Besides, it is important to note the potential inaccuracies of ESMs in simulating subsurface thermodynamics in permafrost regions, as highlighted by Gonzalez-Rouco *et al* (2021). These models might exhibit oversensitivity of the ground thermal regime to atmospheric warming. Although the DICE model does not directly consider the vegetation sink of carbon during permafrost thawing, it combines the decreasing carbon released from land-use changes. We found that some independent studies came up with other possible results. McGuire *et al* (2018) showed that, under RCP4.5, the cumulative change in soil carbon ranged from a 66 GtC loss to a 70 GtC gain, suggesting that increased vegetation carbon sink might offset carbon release from permafrost. Even under RCP8.5, a large net loss of ecosystem carbon may not occur by the end of the 21st century (McGuire *et al* 2018), which may support our findings.

Our investigation involved re-implementing methodologies used by Kessler (2017) and Wirths *et al* (2018), as they utilized earlier versions of the DICE model and employed permafrost area as a proxy. We found that using Kessler's method predicts that more than 55% of permafrost will disappear by 2100, which consequently releases 141 GtC carbon into the atmosphere and the additional warming will be 0.167 °C (figure 4). This prediction is more than four times higher than our findings and significantly surpasses estimates from Koven *et al* (2015). Similarly, employing the method of Wirths *et al* (2018) resulted in predictions stronger than those derived in our study (figure 4). There is significant uncertainty in the prediction of permafrost area loss in the 21st century in previous studies (Miner *et al* 2022). If we follow the rate of permafrost degradation (Dietz *et al* 2021) in the studies of Hope and Schaefer (2016) and Yumashev *et al* (2019), the projected release of permafrost carbon will be significantly lower than that from Kessler's results, by 62% and 51%, respectively, indicating that the impact of uncertainties in degradation rates on the intensity of PCF is direct and substantial. This may confirm that using permafrost area as a connection to assess PCF effects would be questionable.

3.2. Economic impacts

Under the baseline scenario, PCF-induced climate damage costs \$0.008 trillion by 2040, \$0.157 trillion by 2070, and approximately \$0.779 trillion by 2100 (figure 5(a)). The climate damage caused by permafrost thawing is small in the early 21st century but then begins to multiply rapidly. The trend of climate damage is not exactly consistent with the trend of atmospheric temperature increase, possibly because the effects of PCF on economic variables lag slightly behind that of physical variables. This is consistent with the previous studies (e.g. Yumashev *et al* (2019)) because the underlying principles governing climate impact assumptions remain akin, although notable discrepancies exist in the magnitudes reported. Recent studies demonstrated that considerable costs due to the destruction of infrastructure caused by permafrost thaw (Hjort *et al* 2022, Jin *et al* 2024).

In this study, the DICE model that incorporated a permafrost carbon module shows an SCC (social cost of an additional ton of CO_2 emissions) of \$96.1 in 2040, \$192.4 in 2070, and \$330.8 in 2100. These are \$0.94, \$0.95, and \$0.55 (figure 5(b)) higher than the results excluding PCF under the baseline scenario, meaning that thawed permafrost may increase the

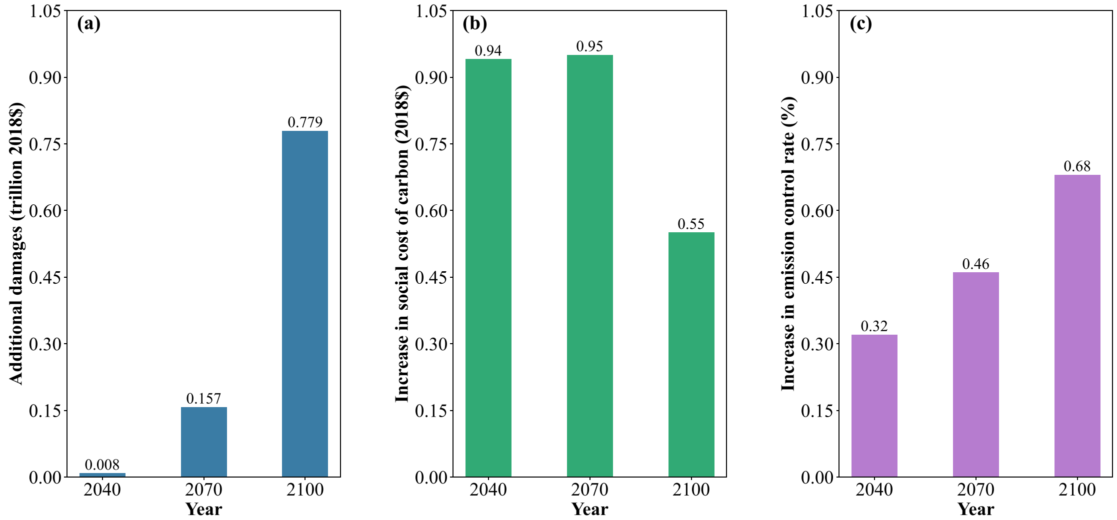

Figure 5. The projection of impact on major economic variables of PCF in the 21st century. (a) The additional climate damage compared with the original results of the DICE model under the baseline scenario. (b) The increase in the SCC under the baseline scenario. (c) The increase in emission control rate under the optimal scenario.

SCC by 0.99%, 0.50%, and 0.17%, respectively. This result shows that PCF plays a positive role in increasing the SCC, even though the increase rate of the SCC decreased gradually after the mid-21st century (which may be related to the change in marginal damages) (Nordhaus 2017). Considering the high sensitivity of SCC to discount parameters and the uncertainty of estimates (Nordhaus 2018b), we reduce the pure social time preference rate to 0.010 and increase the consumption elasticity to 1.5 to run the model. We find that under a lower average discount rate (3.9%) (Barrage and Nordhaus 2023), the SCC predicted by the new model is \$137.60 in 2040, \$276.2 in 2070, and \$476.3 in 2100 (not shown). The additional SCC caused by permafrost thawing is \$1.62, \$1.96, and \$1.98, with an increased ratio of 1.19%, 0.72%, and 0.42%, slightly larger than the value under the original discount rate.

We found that emission control rates (unit: %) are expected to increase on average by 0.40% throughout the 21st century due to the PCF, with 0.32% in 2040, 0.46% in 2070, and 0.68% by 2100 (figure 5(c)) under the optimal scenario. This is because the continued release of additional greenhouse gases from permafrost in the 21st century amplify atmospheric temperatures, causing more climate damage and affecting future welfare. Consequently, it is necessary to strengthen the control of industrial CO_2 emissions in addition to the original emission control rate of greenhouse gases.

3.3. Sensitivity analysis of the edaphic factor in the permafrost carbon module

The *E* factor is a critical parameter in the semi-physical permafrost carbon module. We selected three edaphic factor values (0.025, 0.035, and 0.055 (m^2 ($°C{\cdot}d)^{-1})^{1/2}$) to quantify the uncertainty of the PCF intensity under the baseline scenario in each period of the 21st century. The results predict that the increase in permafrost active layer thickness in the 21st century ranges from 0.22 to 0.49 m, cumulative carbon emissions range from 22.2 to 31.5 GtC (figure 6), and additional warming ranges from 0.027 °C to 0.039 °C (figure S2). Our predictions of the PCF intensity are varied within a limited range but the variation is asymmetrical. Even if the edaphic factor value is higher, it has little effect on the result, and the PCF intensity is still lower than those studies based on permafrost area changes. If the edaphic factor value is smaller than that we used, the PCF intensity may be lower. We also performed sensitivity analysis on the edaphic factor on the economic variables (figures S3–S5), indicating the range of variation is relatively limited.

3.4. Limitations

We mainly considered climate-driven permafrost carbon cycles under natural and undisturbed states. Some processes that would accelerate the degradation of permafrost are not included in our model, such as rapid collapse and wildfires (Walker *et al* 2019, Turetsky *et al* 2020). Because the DICE model considers mainly the interactions between carbon cycles and climate system through global mean annual air temperature, we did not consider the effects of winter processes, where rapid winter warming and changes in seasonal snow conditions can warm permafrost up then thaw faster in summer (Zhang 2005, Park *et al* 2015). Meanwhile, some studies suggested that the Arctic could become wetter in the future (Boisvert and Stroeve 2015, Bintanja *et al* 2020), which might introduce more complexity in predictions of PCF. The

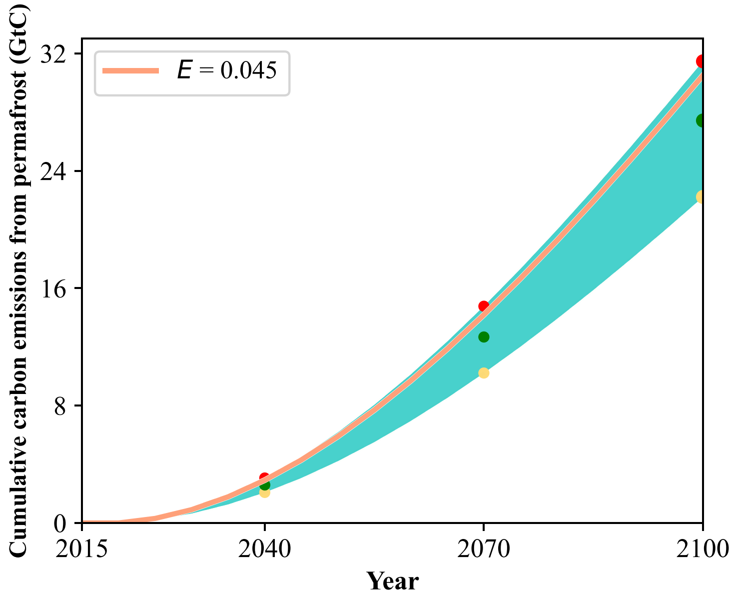

Figure 6. This chart shows the predicted range of cumulative carbon emissions from permafrost in the 21st century under the baseline scenario based on different edaphic factors 'E'. The orange curve represents the projected carbon emissions when the edaphic factor value is 0.045 (m^2 $(°C·d)^{-1})^{1/2}$ by default. The upper and lower boundary of the shade represents the projected carbon emissions when the edaphic factor values are 0.055 and 0.025 (m^2 $(°C·d)^{-1})^{1/2}$, respectively. The red, blue, and yellow dots represent the carbon emissions in each period when the edaphic factor values are 0.055, 0.035, and 0.025 (m^2 $(°C·d)^{-1})^{1/2}$, respectively.

edaphic factor we used is assumed to be constant over the entire period and does not consider the effects of soil moisture changes. In the future, we need to expand the DICE framework to make sure it is able to consider key hydrological cycles.

Spatial features of permafrost thawing are certainly important. However, at this stage, we considered permafrost regions in the NH as a whole. Because the DICE model is an inter-generation optimization model, it requires a relatively simple model structure in order to implement optimization over hundreds of years. Meanwhile, the social and economic processes have different temporal and spatial scales with the natural system. Future research directions aim to address these limitations. Improving the accuracy of our understanding of permafrost regions requires a more nuanced subdivision based on permafrost temperature and a deeper consideration of carbon decomposition processes during cold seasons (Wang *et al* 2023). Extending the active layer thickness estimate method to the entire spatial domain of the permafrost regions and utilizing local temperature anomalies to drive carbon emissions is also worthy of consideration.

4. Conclusions

We incorporated a semi-physical permafrost carbon module into the DICE model and then estimated PCF. We found that under the baseline scenario of the DICE model, CO_2 and CH_4 released from permafrost enhance climate change (about an additional warming of 0.038 °C by 2100) thus increase the economic cost by $0.779 trillion, proportional to the amount of newly released carbon due to permafrost thawing. The results showed that climate-driven permafrost thawing and carbon decomposition are relatively slow. Our study potentially provides a different perspective to scrutinize the climate feedback and related economic impacts due to permafrost thawing. Our results do not aim to deny the importance of PCF in the future but emphasize the necessity of directing more attention to carbon processes during the non-growing season and sudden changes in permafrost (collapse, wildfires, etc). These aspects warrant ongoing consideration and study to comprehensively understand and address the implications of permafrost dynamics on our climate system.

Data availability statement

Data in this study are accessible (a) CRU TS v.4.06 is available at https://catalogue.ceda.ac.uk/uuid/e0b4e1e56c1c4460b796073a31366980 (last access on 20 December 2022, (Harris *et al* 2020)). (b) Circum-Arctic Map of Permafrost and Ground Ice Conditions, Version 2 is available at NASA National Snow and Ice Data Center Distributed Active Archive Center (https://doi.org/10.7265/skbg-kf16, last access on 20 December 2022, (Brown *et al* 2002)). (c) HadCRUT5 Analysis is available at Climatic Research Unit (https://crudata.uea.ac.uk/cru/data/temperature/, last access on 20 December 2022, (Morice *et al* 2021)). The DICE-2016R3 model is available at https://williamnordhaus.com/ (last accessed on 20 December 2022, (Nordhaus 2019)).

The revised model code is available at https://zenodo.org/records/10699552 (last accessed on 24 February 2024, (Wang and Zhu 2024)).

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

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