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Economic carbon cycle feedbacks may offset additional warming from natural feedbacks

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As the Earth warms, carbon sinks on land and in the ocean will weaken, thereby increasing the rate of warming. Although natural mechanisms contributing to this positive climate–carbon feedback have been evaluated using Earth system models, analogous feedbacks involving human activities have not been systematically quantified. Here we conceptualize and estimate the magnitude of several economic mechanisms that generate a carbon–climate feedback, using the Kaya identity to separate a net economic feedback into components associated with population, GDP, heating and cooling, and the carbon intensity of energy production and transportation. We find that climate-driven decreases in economic activity (GDP) may in turn decrease human energy use and thus fossil fuel CO_2 emissions. In a high radiative forcing scenario, such decreases in economic activity reduce fossil fuel emissions by 13% this century, lowering atmospheric CO_2 by over 100 ppm in 2100. The natural carbon–climate feedback, in contrast, increases atmospheric CO_2 over this period by a similar amount, and thus, the net effect including both feedbacks is nearly zero. Our work highlights the importance of improving the representation of climate–economic feedbacks in scenarios of future change. Although the effects of climate warming on the economy may offset weakening land and ocean carbon sinks, a loss of economic productivity will have high societal costs, potentially increasing wealth inequity and limiting resources available for effective adaptation.

carbon cycle feedbacks | climate change | economic damages | integrated assessment models | fossil fuels

Changes in the Earth system as the planet warms are likely to make it progressively more difficult to stabilize the climate (1). For example, decreases in carbon uptake by terrestrial and marine ecosystems could reduce cumulative CO_2 emissions allowable under a 2 °C climate target by 6–29% (2, 3). On land, climate models show a positive carbon–climate feedback primarily from decreases in net primary production in response to warming and drying in the tropics, along with enhanced carbon losses from soils (4–6). In the oceans, increasing stratification weakens anthropogenic carbon flow into the ocean interior, while rising temperatures simultaneously reduce CO_2 solubility (7). Previous studies have quantified the relative importance of different natural feedback processes by using Earth system models to isolate and estimate the gain of the carbon–climate feedback as a function of the models' climate sensitivity, the sensitivity of ocean and land carbon reservoirs to warming, and the sensitivity of these same reservoirs to rising atmospheric CO_2 (8). However, although there are a number of mechanisms by which fossil fuel emissions may be affected by temperature (see, for example, ref. 9), emissions remain an exogenous, temperature-insensitive input to most Earth system models (4, 5). Although some integrated assessment models have explored the connection between temperature and emissions (9–12), the feedback effect from this relationship has not been systematically assessed. As a result, the magnitude of the carbon cycle feedback related to human systems is not well understood.

Climate change will affect human activity, different sectors of the economy, and types of energy infrastructure in different ways, each with the potential to alter fossil fuel CO_2 emissions (Fig. 1). Each of these effects has been analyzed separately to varying degrees by previous studies. Rising temperatures will have direct effects on human mortality through various avenues including heat exposure, disease spread, extreme weather events, and food and water scarcity (13). Climate change will also alter economic productivity through direct effects on labor productivity from heat stress, infrastructure damage, and resource diversion and losses (14). These effects on population and economic output overall tend to indirectly decrease energy use and thus fossil CO_2 emissions. Increased temperatures will also change energy use more directly by influencing heating and cooling demands in residential and commercial sectors, the balance of which determines the overall sign of this effect (15). Additionally, rising temperatures will affect thermoelectric power production, electricity distribution, and transportation systems by decreasing energy efficiency and thereby increasing emissions from fossil fuel-burning infrastructure (16–18).

Integrating various economic effects across different sectors, empirical modeling has recently suggested that temperature may have a strong influence on economic activity, reducing gross domestic production (GDP) by as much as 20% worldwide by 2100 (19). Such large economic effects would in turn decrease energy use and fossil fuel CO_2 emissions. Although other estimates of economic damages under climate change are much smaller, ranging from −1.5 to +2.3% change in GDP per °C (11, 20), such estimates

Significance

The response of different economic sectors and energy infrastructure to climate warming is complex and difficult to compare with land and ocean carbon cycle feedbacks. Our analysis provides a framework for assessing such economic responses and comparing climate feedbacks in integrated assessment and earth system models. A better understanding of the potential effect of an economically driven feedback may improve our ability to estimate limits on cumulative emissions necessary to meet specific climate stabilization targets. We find that a net negative feedback from economic damages on fossil fuels may be strong enough to offset the positive feedback from terrestrial and marine ecosystems; however, these economic losses may disproportionately affect vulnerable populations and make climate mitigation more difficult.

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The authors declare no conflict of interest.

Data deposition: All code used to generate the results is available on GitHub (https://github.com/dawnlwoodard/econ-feedbacks.git).

See Commentary on page 714.

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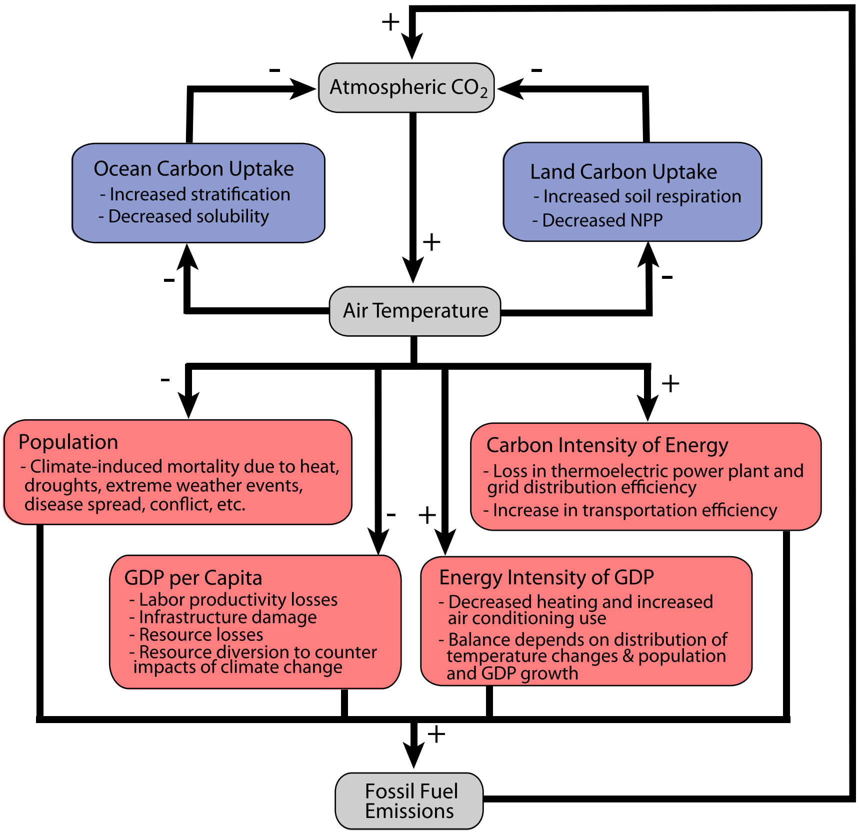

Fig. 1. Diagram of the relationship between the economic and natural carbon cycle processes considered in this analysis. In our model, we included carbon–climate feedbacks on the natural carbon cycle from warming effects on ocean stratification, soil decomposition, and net primary productivity (NPP). We then used this base model to explore effects from global temperatures on the economic carbon cycle through population, GDP, the energy intensity of GDP, and the carbon intensity of energy. These effects translate into a temperature-driven effect on fossil fuel emissions through the Kaya identity (Eq. **1**) in our model, which then has consequences for atmospheric CO_2 and land and ocean uptake of carbon, as well as temperature. The signs shown indicate a net direct (+) or inverse (–) relationship between each upstream and downstream process in our model. Further discussion of the uncertainty of the signs of the economic relationship is given in *SI Appendix*, *SI Materials and Methods*.

often rely on theoretical and sometimes arbitrary damage functions (21–24) rather than historical observations.

The combination of temperature-driven effects on population, energy, and GDP generates an economic carbon–climate feedback because of the direct connection between economic activity and fossil fuel emissions. This feedback is an economically driven parallel to the natural carbon–climate feedback operating through land and ocean processes. Through its influence on atmospheric carbon dioxide, the economic carbon–climate feedback may subsequently modify processes regulating natural carbon–concentration and carbon–climate feedbacks, including, for example, photosynthesis and air–sea gas exchange that are sensitive to rising CO_2 and climate warming.

Here we systematically compare economic and natural carbon cycle feedbacks to estimate the carbon cycle implications of human responses to climate change and especially the recent estimates of climate-related economic damages (19). We conceptualize drivers of the economic carbon–climate feedback through the Kaya identity, using a set of scenarios to isolate feedbacks on population (hereafter referred to as our population scenario), GDP per capita (GDP scenario), the energy intensity of GDP (energy intensity scenario), and the carbon intensity of energy (carbon intensity scenario) individually, as well as a scenario combining GDP and carbon intensity processes (net economic scenario). We also include a baseline (no feedbacks scenario), which allows natural carbon fluxes in our model to respond to rising CO_2 but not to rising temperatures, and a scenario that includes only natural carbon–climate feedback processes (net natural scenario). Previous work has referred to this latter scenario as fully coupled (for example, refs. 4 and 5), but we reserve the term fully coupled here for our final scenario, which is the combination of the net natural and net economic scenarios (see *SI Appendix*, Table S1, for more detail on our simulation design).

For our baseline forcing data, we use historical socioeconomic data and assume future fossil fuel CO_2 emissions and energy and population projections from the Global Change Assessment Model (GCAM) simulation for Representative Concentration Pathway 8.5 (RCP8.5) (25, 26). Relationships between temperature and each economic component are derived from a literature synthesis, whereas for the natural carbon cycle we optimize a box model to match the mean carbon cycle behavior of fully coupled Earth system models (4, 27).

Results

Climate and Carbon Cycle Effects. Relative to our baseline scenario, the natural carbon–climate feedback (net natural) increased atmospheric CO_2 by 92 ppm (56–152 ppm), or about 15%, and temperature by 0.30 °C (0.19 °C–0.44 °C) from 1800 to 2100. The economic feedback (net economic), in contrast, decreased CO_2 by 85 ppm (ranging from an increase of 3.3 ppm to a decrease of 204 ppm), or 14%, and temperature by 0.29 °C (ranging from an increase of 0.01 °C to a decrease of 0.76 °C) over the same period. The combination of these two sets of effects in our fully coupled scenario reduced CO_2 by about 12 ppm (ranging from an increase of 156 to a decrease of 179 ppm) and had only a

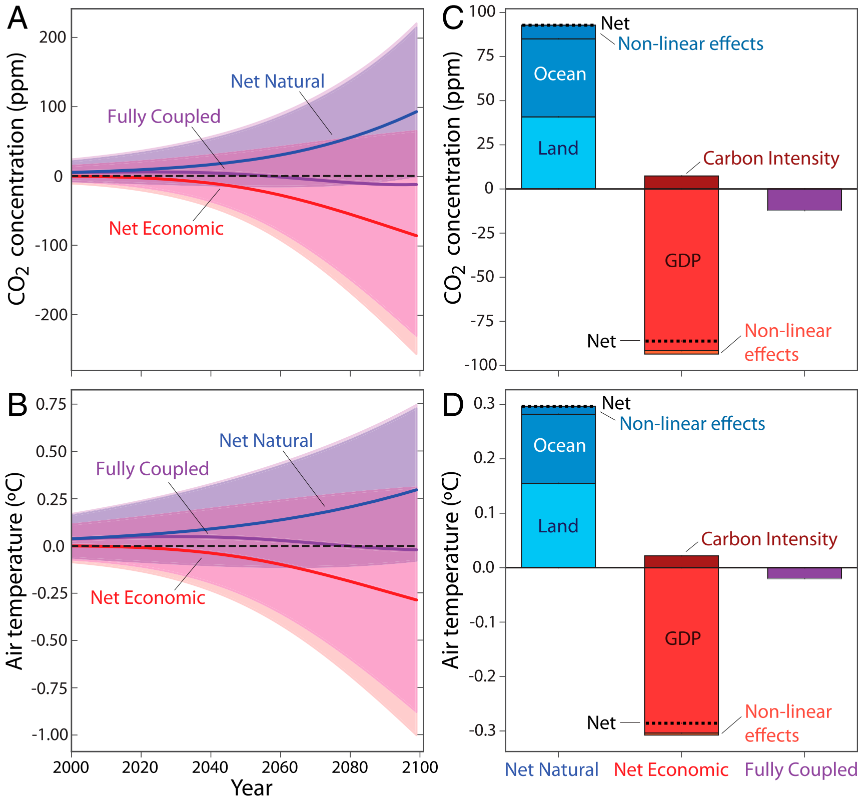

Fig. 2. Net effects of including only natural, only economic, or both sets of feedbacks in our model compared with the baseline (no feedbacks) scenario. All values shown are given as the difference between the baseline and that scenario. (*A* and *B*) Air temperature and atmospheric CO_2 over the 21st century with uncertainty bounds on the fully coupled and net economic scenarios. Natural carbon–climate feedbacks (net natural) increased atmospheric CO_2 and temperature, whereas economic feedback processes (net economic) decreased them. The net economic effect more than offset the net natural, so the fully coupled scenario showed an overall negative effect on temperature and atmospheric CO_2. (*C* and *D*) The change in temperature and atmospheric CO_2 from 1800 to 2100 for these scenarios along with decompositions of the contributions to each net effect. For the natural carbon cycle, effects from the land and ocean in our model were similar in magnitude. Temperature effects on GDP drove the net economic effect strongly down, and although the carbon intensity of energy (carbon intensity) response caused a slight increase, the overall effect was dominated by GDP. Both net natural and net economic simulations also had some nonlinear interaction effects that were not captured by our decoupled scenarios.

minor effect on temperature (Fig. 2 and *SI Appendix*, Table S3). Here the response of economic processes to climate warming has not only compensated for the positive feedback from natural carbon–climate interactions but has driven the entire system toward a small negative feedback.

For both economic and carbon cycle parameters we derived upper and lower uncertainty bounds and propagated them through our model. Our upper bound on the relationship between GDP and temperature comes from the highest-impact scenario in Burke et al. (19), and our lower bound is the damage function from the Dynamic Integrated Climate-Economy (DICE) model (11). For uncertainty related to climate effects on carbon intensity, we derived upper and lower bounds from estimates reported in the literature (see *SI Appendix*, *SI Materials and Methods*, for details). For our population and energy intensity scenarios we assumed upper and lower uncertainty bounds of ±50% because significant uncertainties exist in the current understanding of these relationships in the literature.

Natural carbon cycle uncertainty estimates were derived from fitting to ±1 SD of the fifth Phase of the Coupled Model Intercomparison Project (CMIP5) multimodel mean ocean and land carbon storage by 2100. A more detailed description of uncertainty in each scenario is available in *SI Appendix*, *SI Materials and Methods*.

Our results demonstrate the potentially comparable magnitude of an economic carbon–climate feedback and indicate that this may act to substantially counter warming from the natural carbon–climate feedback. This apparent benefit to the climate is driven by large economic losses, so although we find that economic feedback processes do have the capacity to balance the additional warming from the natural carbon–climate feedback, this is achieved only through damages to the global economy.

Carbon fluxes, atmospheric CO_2 levels, and global mean surface temperatures in our fully coupled scenario were lower than in the net natural scenario, particularly as temperatures increased more rapidly after 2050 (Fig. 3 *A*–*C*). By 2100, economic damages from climate warming reduced GDP by 22% (5.9–61%) (*SI Appendix*, Table S2), which in turn (in the GDP scenario) lowered cumulative fossil fuel emissions by 304 Pg C (ranging from a decrease of 731 Pg C to an increase of 44 Pg C) or 14% (Fig. 3*D*). Temperature-driven decreases in the efficiency of energy production from fossil fuels increased the carbon intensity of energy in our model by 2.4% (ranging from a decrease of 0.51% to a decrease of 6.6%), which alone (in the carbon intensity scenario) drove a 24 Pg C increase (ranging from a 6 Pg C decrease to a 58 Pg C increase) in cumulative emissions relative to the baseline by the end of the century. This positive influence on emissions associated with climate effects on the carbon intensity of energy was more than offset by the negative effect of climate on GDP, so that together, economic processes in our fully coupled scenario reduced atmospheric CO_2 by 104 ppm (ranging from a decrease of 235 ppm to an increase of 3 ppm), or 15%, and global mean air temperature by about 0.32 °C (ranging from a decrease of 0.82 °C to an increase of 0.01 °C) from 1800 to 2100 relative to the net natural scenario (Fig. 3). This effect on the carbon cycle is comparable in magnitude, but

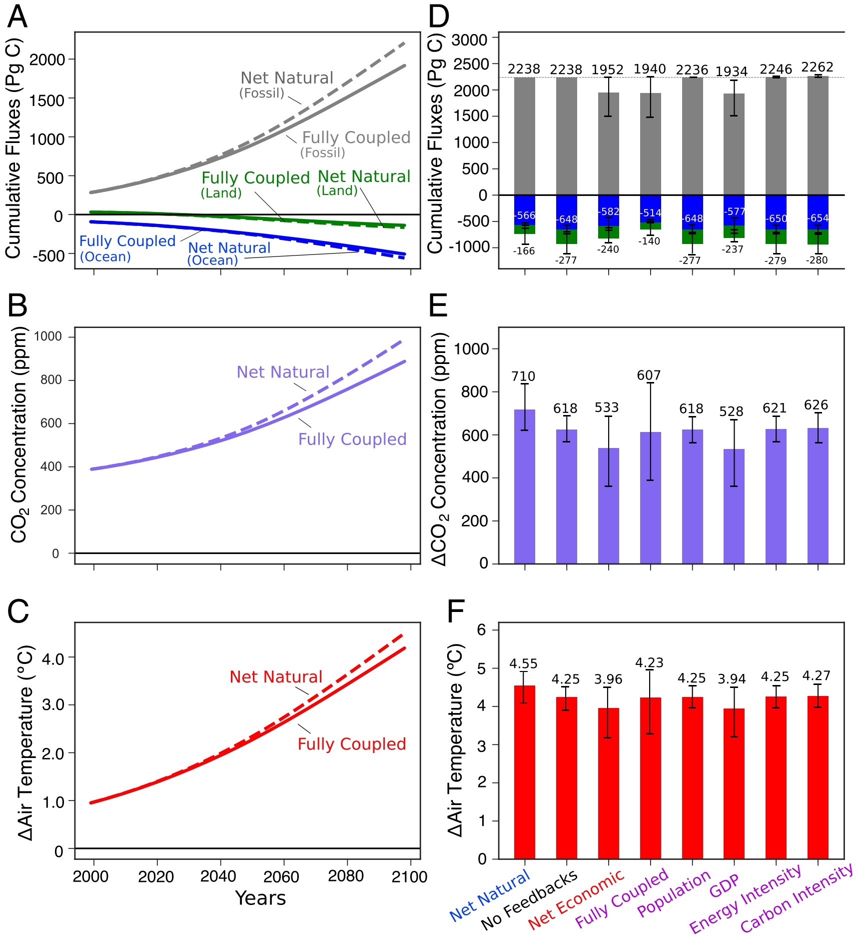

Fig. 3. A comparison of different economic and natural carbon cycle feedbacks on the Earth system. (*A*–*C*) The effect on the carbon cycle of including economic feedback effects over the 21st century. Our fully coupled scenario (solid), which includes both natural and economic carbon–climate feedbacks, has lower emissions, atmospheric CO_2, and temperature than our net natural scenario (dashed), which includes no temperature effects on fossil fuel emissions. These effects are seen most strongly in the latter half of the century when temperature increases are larger. (*D*–*F*) Changes in cumulative fluxes, atmospheric CO_2 concentration, and temperature for each scenario from 1800 to 2100. The net natural carbon–climate feedback drives atmospheric CO_2 and temperature above the no feedbacks scenario baseline, whereas the net economic feedback lowers these values below baseline. Our GDP and population scenarios both result in negative effects on emissions, although the GDP effect is considerably more pronounced, whereas our energy intensity and carbon intensity scenarios contribute to slight increases in fossil fuel emissions.

opposite in sign, to potential losses in permafrost over the next century (28).

In two other decoupled economic scenarios, we examined how climate change effects on energy demand and population may influence carbon cycle processes. In our analysis, the contribution of each of these two components to economic effects on the carbon cycle was only very slight (Fig. 3 *D*–*F*).

Feedback Effects. Integrating economic processes into our model changed the sign and magnitude of the gain of the carbon–climate feedback because of the relatively strong temperature sensitivity of fossil fuel emissions. We illustrate this sensitivity in Fig. 4. In our model, a 1% decline in fossil fuel emissions per °C of climate warming corresponded to a decrease in the gain of the carbon–climate feedback of about 0.05, a decrease in atmospheric CO_2 of 28 ppm compared with our net natural scenario, and a feedback-driven temperature decline of 0.1 °C by 2100. Although the sensitivity function was nonlinear, we fit a linear model through our upper and lower bounds from our fully coupled scenario to estimate this unit effect. Because our fully coupled scenario had an average emissions sensitivity of about −3% per °C, this reduced the gain of the carbon–climate feedback from a positive value in our net natural scenario (+0.13) to slightly below zero in our fully coupled scenario (−0.02) (Fig. 4 and *SI Appendix*, Table S3).

Discussion

Our results indicate that the economic feedback has the potential to reverse the sign of the overall carbon–climate feedback, but the significance of the effect is highly sensitive to the relationship between climate and GDP. If the effect of climate on GDP is large and dominates the feedback, the economic carbon feedback counteracts the response of the natural carbon cycle. However, if this temperature–GDP effect is more in line with estimates like those in the 2016 version of DICE model (11), we can expect that the economic contribution to the carbon–climate feedback will instead add slightly to the natural positive gain (Fig. 4), somewhat increasing future temperatures and atmospheric carbon dioxide (Fig. 3*A*).

Our estimate of climate effects on fossil emissions is substantially higher than a previous analysis from the Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model, which found a reduction in CO_2 emissions of 4.7% from their economic feedbacks by 2100 (9). This is likely driven by the choice of economic damage function. The damages found by Burke et al. (19) are larger than those used in ENVISAGE as well as those used

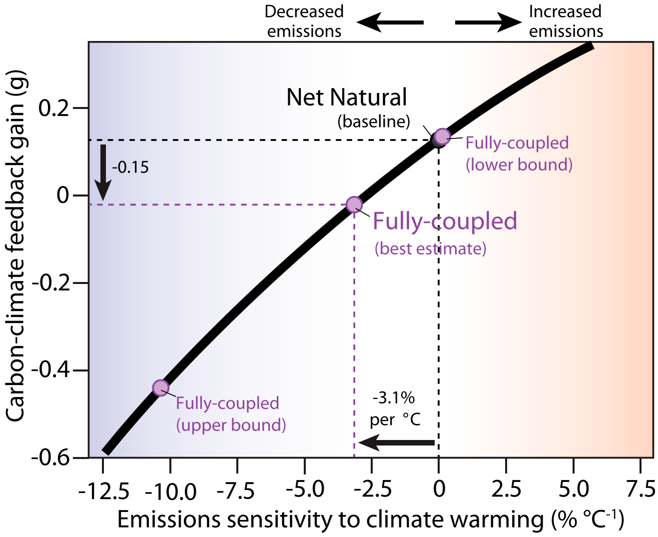

Fig. 4. The carbon cycle response to economic damages in our model under RCP8.5. The black curve was derived by simulating a range of potential emissions damages per degree (shown along the *x* axis) in our model and computing the resultant cumulative carbon–climate feedback gain over the period from 1800 to 2100. The steep slope of the curve suggests that even small changes in the temperature sensitivity of fossil fuel emissions may have significant consequences for the carbon cycle. Overlaid on the curve are points showing specific results from our fully coupled and net natural scenarios. Comparing these scenarios shows the overall effect on the carbon cycle of including an economic carbon–climate feedback in our model. The fully coupled scenario has an approximate fossil fuel temperature sensitivity of −3.1% per °C, resulting in a decrease in the gain of 0.15 from the net natural scenario.

in many other models because Burke's analysis broadly includes any climate-driven effects that would be reflected in GDP over the past half century. The sum of the effects considered in ENVISAGE we expect to be lower because only certain economic sectors were included. For example, both extreme weather and catastrophic events are not included in the ENVISAGE simulations (29), whereas the GDP damages from Burke et al. (19) are general enough to include such effects.

By propagating upper and lower uncertainty bounds for each term in the Kaya identity through our model, we have attempted to illustrate the spread of potential outcomes. Additionally, although we have made every effort to use reasonable values, it was necessary to make several major assumptions to maintain the simplicity of our model and not attempt to replicate a full integrated assessment model, because that is beyond the scope of this work. A key future challenge is to quantify economic carbon–climate feedbacks within and across integrated assessment models that account for more complex interactions among different sectors and processes.

Improving estimates of the economic carbon–climate feedback is particularly relevant because important tradeoffs exist with respect to the societal effects of strong versus weak economic damage functions. Although a stronger damage function in response to rising temperature appears to imply that it may be easier to match emissions reductions targets, this comes at an economic cost that would likely make it more difficult for vulnerable regions to respond to climate change effects (30). Moreover, such economic and social costs entailed by stronger damage functions are likely to be large and inequitably distributed because climate change is expected to worsen already existing economic vulnerabilities (31). Natural disasters, for example, have higher death tolls in lower-income areas and in countries without democratic institutions (32). In our globally averaged model, the Burke et al. relationship led to GDP losses of 22% by 2100 (*SI Appendix*, Table S2). In just the United States by the end of the century, the poorest third of counties are predicted to experience losses of 2–20% of income, whereas the richest third may experience losses of only 7% up through potential benefits of 1.2% of income (33). Any potential benefit in terms of lower emissions from a negative economic feedback only exists because nations necessarily lose so much productivity, in the form of human lives, agriculture, infrastructure, and labor, that this reduction in economic activity lowers their fossil fuel emissions.

Strong versus weak economic damage functions also may have implications for the distribution of climate effects across natural and human systems. A weaker economic damage function, for example, would allow more CO_2 to accumulate in the atmosphere, causing higher surface air temperatures. Accelerated warming, in turn, would cause greater damages in terrestrial and marine ecosystems, including losses of net primary production and biodiversity on land (34) and the disruption of critical nutrient supply pathways in the ocean (35). Thus, although natural and economic feedbacks are likely opposite in sign, carbon–climate feedbacks driven by higher temperatures have net damaging effects on both natural and human systems.

The strength of both economic and natural feedbacks varies significantly over the globe, so regional carbon cycle effects may be considerably stronger or weaker than the global mean (19, 36). Economic activities driving the carbon–climate feedback at the local level will include changes in tourism revenue, damages from sea level rise and wildfires, and locally varying patterns of energy use. For example, Isaac and Van Vuuren (37) found that India showed a very strong effect of temperature on energy demand, in contrast to their finding of a much less significant effect globally. The economic climate feedback from energy use would overall be expected to be higher in areas with quickly increasing GDP and population as well as larger predicted climate effects.

In the model used here, we have considered a limited number of both natural and economic processes. We tuned our simple natural carbon cycle model to match the mean behavior of the CMIP5 models, but these models are missing key natural processes such as the permafrost carbon reservoir and its sensitivity to thaw (28) and are weak in their representation of other drivers of the carbon–climate feedback including the representation of ecological tipping points within the Amazon (38). On the economic-driven side, we do not include any feedbacks associated with climate effects on land use. Recent work indicates these would be expected to contribute to a positive economic carbon–climate feedback (39), mitigating slightly the negative effects of the GDP feedback described here. It is also worth acknowledging that there are other human-driven feedbacks that fall outside of the carbon–climate feedback. One example is an economic carbon–concentration feedback associated with the benefits of increasing atmospheric CO_2 on crops. There are also potential economic effects associated with climate-driven human migration, which could have varied effects on climate through both carbon and noncarbon pathways. Beyond carbon feedbacks entirely, there may be policy-driven feedbacks that influence aerosols and albedo.

Our results provide a baseline effort to assess the economic carbon–climate feedback and compare it to the natural feedback by unifying the different contributing mechanisms and processes within a single framework. More broadly, we show how methodology for carbon cycle feedback analysis can be extended to the economic sector, for future assessment of integrated assessment models. Our model results have demonstrated that an economic carbon–climate feedback has the potential to significantly counteract the warming contribution of land and ocean feedbacks; however, the benefits of this negative economic feedback in terms of the carbon cycle will likely be offset by substantial economic and societal costs. Earth system models that neglect these economic feedback processes may significantly overestimate the carbon–climate feedback. Future research to better characterize the nature and scale of economic disruptions from climate change will reduce uncertainty and allow this feedback to be better incorporated into integrated assessment and Earth system models.

Materials and Methods

Details of our analytic method are available in *SI Appendix*, *SI Materials and Methods*. All code used to generate the results is available on GitHub (40). Briefly, we represent the natural carbon cycle—including key carbon–climate and carbon–concentration feedbacks—using a global box model of the atmosphere, land, and ocean carbon system (*SI Appendix*, *SI Materials and Methods*). We tuned the model to within 1 SD of the mean behavior of Earth system models from the CMIP5 (*SI Appendix*, Tables S4 and S5), and it reasonably reproduces observations of the carbon cycle and temperature over the past 2 centuries (*SI Appendix*, Fig. S1). Economic feedback effects are explicitly incorporated in the model as effects on different factors of the Kaya identity:

$$F = P \cdot \frac{G}{P} \cdot \frac{E}{G} \cdot \frac{F}{E}, \qquad [1]$$

where F represents global fossil fuel CO_2 emissions; P is population; G is world GDP or gross world product; E is global energy consumption; and E/G and F/E are the energy intensity of GDP and the carbon intensity of energy, respectively. As a baseline, we use historical socioeconomic data (*SI Appendix*, Fig. S2 and Table S6) and assume future fossil fuel CO_2 emissions and energy and population projections from the GCAM simulation for RCP8.5 (25, 26). Relationships with temperature for each economic component are derived from previous studies (*SI Appendix*, *SI Materials and Methods* and Fig. S3).

We isolate and estimate the magnitude of carbon cycle feedbacks by restricting in turn the various components of the coupled model following methodology established for natural carbon cycle analysis (5, 8). All scenarios include natural carbon–concentration feedback processes, but carbon–climate feedbacks are isolated in different scenarios as summarized in *SI Appendix*, Table S1. The no feedbacks scenario is our baseline for comparison and includes only natural carbon cycle responses to rising atmospheric CO_2, neglecting both human responses and land and ocean responses to warming. The net natural scenario corresponds to the fully coupled scenario in previous analyses of the natural carbon cycle (4, 5) in which all natural feedbacks are allowed to operate, but all economic responses to warming are excluded. The population scenario adds estimates of climate-related deaths (but no other human responses) (41) onto the baseline scenario. The energy intensity scenario includes only modeled changes in energy demand for heating and cooling of residential and commercial buildings (following ref. 37) on top of the baseline. The carbon intensity scenario includes only temperature-related changes in the efficiency of electricity production, electricity distribution, and transportation (16, 17, 42–44) (*SI Appendix*, *SI Materials and Methods*, Fig. S4, and Table S7 for details) in addition to the baseline. The GDP scenario incorporates economic damages due to climate change, using the nonlinear relationship found by Burke et al. (19) as a best estimate. The net economic scenario is the economic parallel to the net natural and includes carbon intensity responses and GDP responses (i.e., effects on the Kaya factors G/P and F/E, which influence emissions in opposite directions as temperature increases) but excludes our independent estimates of population and energy intensity responses because these may be subsumed into GDP damages. Finally, our fully coupled scenario combines the net natural and net economic scenarios to include both economic and natural carbon–climate feedbacks on top of the baseline scenario.

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