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Analysis

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The historical social cost of fossil and industrial CO_2 emissions

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Past CO_2 emissions have been causing social costs and continue to reduce wealth in the future. Countries differ considerably in their amounts and time profiles of past CO_2 emissions. Here we calibrate an integrated assessment model on past economic and climate development to estimate the historical time series of social costs of carbon and to assess how much individual countries have reduced global wealth by their fossil and industrial-process CO_2 emissions from 1950 to 2018. Historical social costs of carbon quantify the long-lasting wealth reduction by past CO_2 emissions, which we term 'climate wealth borrowing', as economic output has been generated at the expense of future climate damages. We find that the United States and China have been responsible for the largest shares of global climate wealth borrowing since 1950, while the per-capita pattern is quite different.

The major cause for climate change, elevated atmospheric CO_2 concentration, did not happen overnight, but is the result of past CO_2 emissions. These past CO_2 emissions brought economic wealth for the emitting countries, but have caused and will cause climate damage worldwide in the past, present and future. In an inclusive wealth (IW) perspective[1], an intact climate system is a valuable asset, and the climate damages caused by CO_2 emissions reduce the wealth associated with this asset, the 'climate wealth'. Past CO_2 emissions generated economic wealth at that time, at the expense of reduced climate wealth, and in that sense they have been borrowed from climate wealth. To capture this, we propose the concept of climate wealth borrowing (CWB), which is the present value, in consumption equivalents, of climate damages caused by all historical CO_2 emissions.

Countries have been differing considerably in their amounts and time profiles of past CO_2 emissions[2]. While from a cumulative emissions perspective, the emissions time profile does not matter[3], it does from a welfare-theoretic perspective[4], due to (1) increasing marginal damages of CO_2 emissions and (2) discounting. (1) Whereas each ton of CO_2 contributes similarly to global warming[5,6], climate damages increase more than proportionally with the temperature increase[4]. Hence, marginal damages, that is, the extra climate damages due to an extra ton of emissions, were considerably smaller at lower atmospheric CO_2 concentrations in the past. (2) However, having emitted CO_2 in the past also means that these emissions have caused damages already in the past and thus had 'more' time in accumulating impacts on wealth. The CWB concept includes both of these effects and allows a welfare-theoretically sound assessment of past CO_2 emissions.

In this analysis, we apply the CWB concept in the context of IW and comprehensive investment assessments[7–9]. The IW approach defines the inclusive (or comprehensive) wealth as the aggregate value of all natural and human-made capital stocks[7]. The IW approach is applied in the UN IW reports[10–12] and the United States have recently launched a new draft National Strategy to improve its statistical description of economic activity and development by accounting for the wealth contributions of water, air, and other natural assets following the IW approach[13]. The application of the IW approach allows one to measure how human activities, such as emitting CO_2, affect the various natural and human-made capital stocks and therefore IW over time. As, in particular, natural capital stocks provide various services that are either not traded on markets or accrue outside the national accounting system, and therefore lack price information, the appropriate valuation approach is carried out by means of shadow prices, which capture both use and non-use values of capital stocks[14,15]. CO_2 emissions enter such calculations as cost, anticipating the negative effects of future climate change on most countries around the globe[16]. The associated shadow price of atmospheric CO_2 is coined the social costs of carbon (SCC). Whereas the SCC can be meaningfully derived for any emissions trajectory (for example, any representative concentration pathway), they

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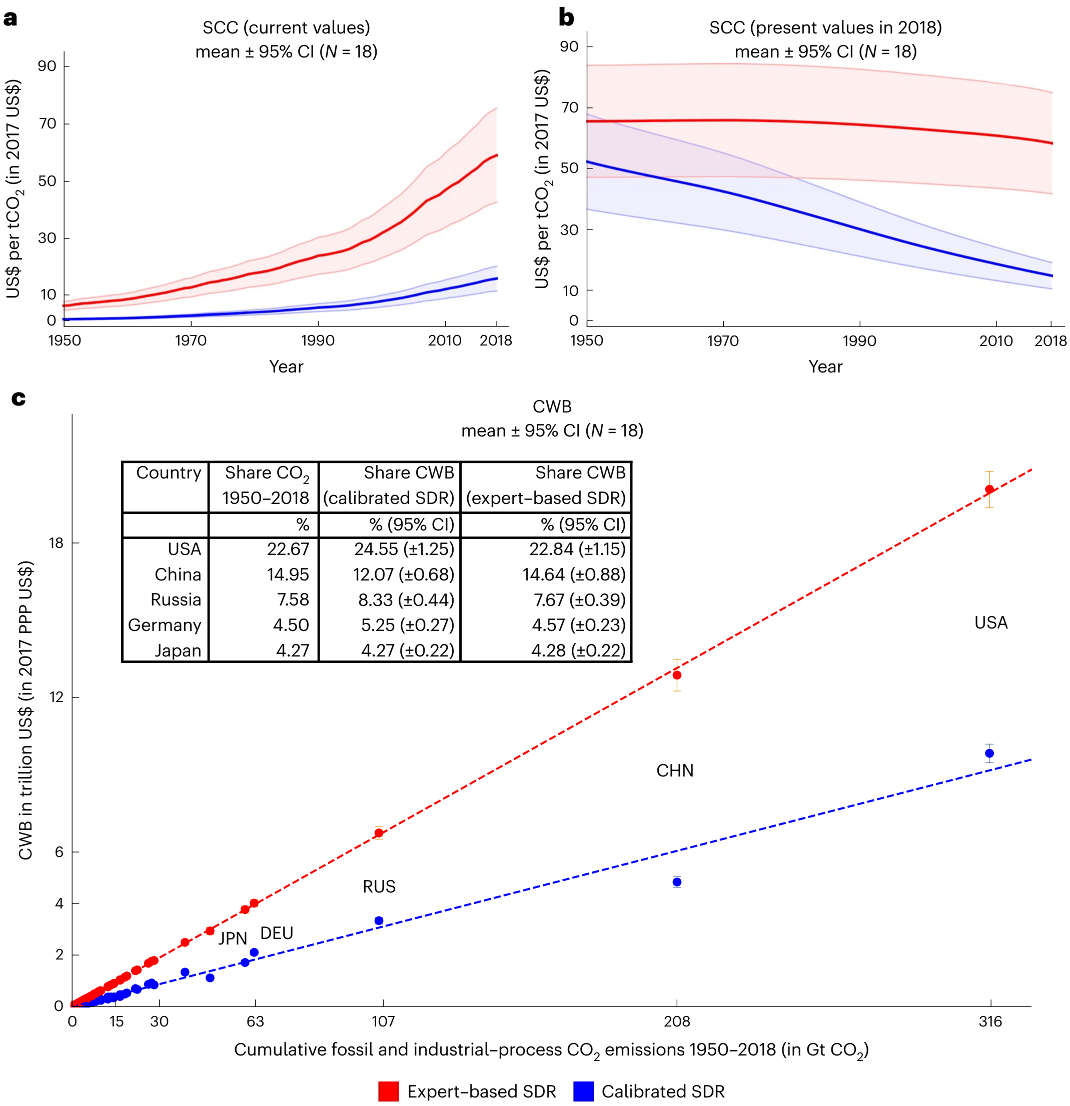

Country	Share CO_2 1950–2018	Share CWB (calibrated SDR)	Share CWB (expert-based SDR)
	%	% (95% CI)	% (95% CI)
USA	22.67	24.55 (±1.25)	22.84 (±1.15)
China	14.95	12.07 (±0.68)	14.64 (±0.88)
Russia	7.58	8.33 (±0.44)	7.67 (±0.39)
Germany	4.50	5.25 (±0.27)	4.57 (±0.23)
Japan	4.27	4.27 (±0.22)	4.28 (±0.22)

🟥 Expert-based SDR 🟦 Calibrated SDR

Fig. 1 | SCC and CWB 1950–2018. a,**b**, The solid lines show the mean SSC in current values at the year of emission (**a**) and present value in 2018 (**b**), with bands indicating 95% CIs of the mean ($N = 18$). **c**, The dots show the relationship between cumulative fossil and industrial-process CO_2 emissions (in Gt CO_2) and the CWB (in trillion USD) for all countries (labels only for the five countries with the largest cumulative emissions and CWB). The error fences display the 95% CIs of the mean ($N = 18$). For the five largest emitters, the relative shares are displayed in the data table in **c**. The dashed lines show a linear model fit on the relationship between cumulative emissions and CWB. All results are presented for the two specifications of the SDR, the expert-based SDR obtained from Drupp et al.[21] (red, $\delta = 1.1\%$ per year and $\eta = 1.35$) and the calibrated SDR (blue, $\delta = 4.4\%$ per year and $\eta = 1.2$). USA, the United States; CHN, China; RUS, Russia; DEU, Germany; JPN, Japan.

coincide only with the optimal (Pigouvian) carbon tax along an optimal emission trajectory[16]. Here we compute a SCC time series and use it to quantify CWB for the historical, non-optimal CO_2 emissions. CWB can be compared with investment in (manufactured) capital[17]. The former reduces global IW (in almost all countries around the globe), and the latter increases IW, through the increase in the investing country's wealth. We put country-specific CWB into perspective with private accumulation of IW arising from the increase of manufactured capital stocks as measure how CWB affects sustainable development of countries.

Deriving the SCC since 1950

To obtain a historical SCC time series and to assess the impact of countries' past CO_2 emissions on global wealth, we calibrate a globally aggregated neoclassical growth model to match observed global economic development, global CO_2 emissions, atmospheric CO_2 concentration and global mean temperature increase from 1950 to 2018. The model structure is based on the integrated assessment model (IAM) DICE[4]. We impose until 2018 the observed paths for investment and CO_2 emissions abatement and consider optimal policies thereafter, as standard in the integrated assessment literature[4]. Two important determinants of the SCC are future economic impacts of climate change and the social discount rate (SDR). In addition to the estimates of economic climate impacts used in DICE[4], we consider alternative climate impact functions based on Weitzman[18] and Howard and Sterner[19]. The latter has been shown to support an ambitious temperature stabilization target comparable to the one set out in the Paris Agreement[20]. We calibrate the central parameters determining the SDR, namely the pure rate of time preference (δ) and the marginal elasticity of utility (η), to match the historical path of investment from 1950 until 2018. This results in an SDR of 6.75% per year for that period. An alternative parameterization derives from the expert survey by Drupp et al.[21], which translates into an SDR of 3.74% per year for that period. Accordingly, we refer to the former as the calibrated, rather high SDR and to the latter as the expert-based, rather low SDR.

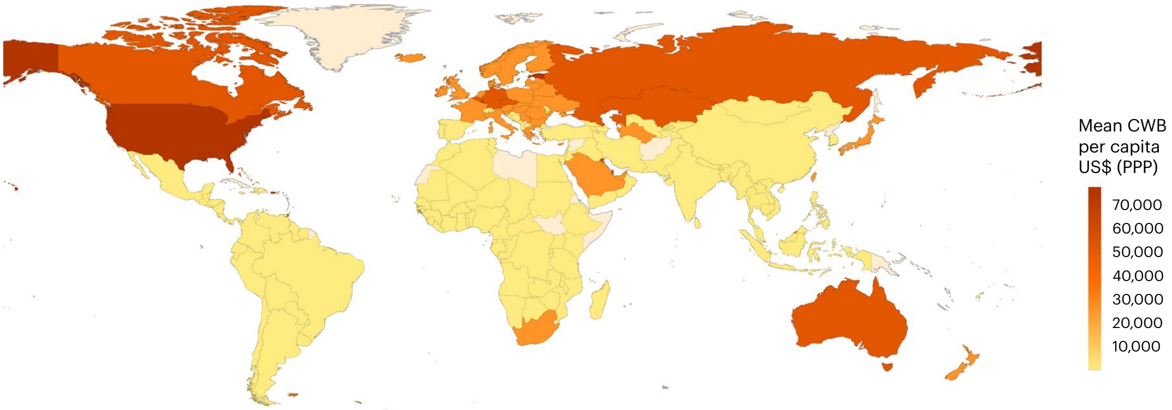

Fig. 2 | Per-capita CWB for the expert-based SDR, in 2017 PPP USD. The figure has been created using Wolfram Research, Inc., Wolfram|Alpha Knowledgebase, Champaign, IL (2021).

CWB

SCC in 1950 have been fairly low compared with SCC in 2018, but clearly positive, reflecting the long-lasting climate effects of past CO_2 emissions. Over time, the current-value SCC increase, reflecting increasing marginal damages (Fig. 1a). From the present-day perspective (2018 in our computations), past CO_2 emissions are valued relatively high, due to the reversed discounting effect: The earlier one would have avoided the emissions and the damage associated, the better from the present value perspective due to the compounding effect. This effect is more pronounced for the higher, calibrated SDR; for the expert-based, lower, SDR, the two opposing effects of compounding and increasing marginal damages almost fully offset each other, resulting in an almost constant present value SCC over time (Fig. 1b). In turn, for the expert-based SDR, CWB scales linearly with cumulative CO_2 emissions (Fig. 1c). For the calibrated, higher, SDR, the compounding effect dominates and historically earlier CO_2 emissions result in higher CWB than more recent CO_2 emissions, which is indicated by the declining present value SCC (Fig. 1b). However, even for a high SDR, the relationship between CWB and cumulative CO_2 emissions is linear with good approximation (Fig. 1c). Thus, valuing cumulative past carbon emissions at current SCC would provide a robust first-order approximation to CWB. Such an approach, that is, using a constant, current SCC estimate to assess past CO_2, is applied in the IW Reports, which assess the cumulative CO_2 between 1990 and 2014 with a constant SCC (for example, ref. 12). Our results show that this approach is a reasonable approximation to the welfare-theoretically sound CWB assessment based on historical SCC.

Mean aggregate CWB amounts to 40.05 (95% confidence interval (CI) ±1.44) and 87.92 (95% CI ±3.23) trillion USD (in 2017 purchasing power parity (PPP) prices) for the calibrated and expert-based SDR, respectively (note that these figures include all fossil and industrial CO_2, for example also international bunker fuel emissions; if we restrict the CO_2 emissions to those attributed to countries, the two figures would drop to 38.86 (95% CI ±1.40) and 85.30 (95% CI ±3.12) trillion USD). The United States and China are responsible for close to 40% of mean aggregated CWB since 1950: the mean United States share is 24.55% (95% CI ±1.25%) and 22.84% (95%CI ±1.15), China's mean share is 12.07% (95% CI ±0.68%) and 14.64% (95% CI ±0.88%) for the calibrated and expert-based SDR specification, respectively. These shares relate to the shares in the cumulative fossil and industrial-process CO_2 emissions (1950–2018) of the United States and China, 22.67% and 14.95%, respectively. Results for all countries can be found in Supplementary Table 1.

Country-specific CWB is the present value of all damages caused by historical CO_2 emissions by that country. This can be compared with the present value of damages resulting from the fraction of atmospheric CO_2 that can be attributed to a country. Based on the FaIR-Geoffroy climate carbon cycle model, only 54% of the United States cumulative emissions between 1950 and 2018 are still in the atmosphere in the year 2018. In comparison, the fraction for China is 63%. Valuing the stock of atmospheric CO_2 attributable to cumulative emissions of the United States at current SCC gives estimates that are 73.90% (95% CI ±21.45%) or 50.14% (95% CI ±14.34%) lower than the emission-based CWB for the calibrated and expert-based SDR specification, respectively. For China the corresponding figures are 59.53% (95% CI ±17.33%) and 40.68% (95% CI ±11.72%) (Extended Data Fig. 1).

Per-capita CWB

While the country-specific CWB is highest and of similar magnitude for the United States and China, the per-capita figures are quite different. Whereas mean per-capita CWB (at current population size) in the United States is 30,061.01 (95% CI ±1,085.80) and 61,399.96 (95% CI ±2,136.10) USD (in 2017 PPP prices) for the calibrated and expert-based SDR; the corresponding figures for China are 3,386.80 (95% CI ±145.10) and 9,014.09 (95% CI ±432.28) USD. Accordingly, on per-capita basis, the United States rank third among all countries of the world (behind Estonia and Luxembourgh), while China falls to the 83rd and 80th place, for the calibrated and expert-based SDR specification, respectively (of 174 countries assessed on per-capita basis). The per-capita assessments confirms the dominant responsibility of industrialized countries for climate change (Fig. 2 displays the mean per-capita CWB for all countries for the expert-based SDR; the corresponding information for the calibrated SDR is shown in Extended Data Fig. 2).

Relationship to manufactured capital wealth investments

Sustainable development, defined as non-declining human wellbeing, requires that IW does not decline[7]. IW is the aggregate social value of all natural and human-made capital stocks. Whereas CWB is a reduction of IW, investments in manufactured capital increase IW. To assess country-specific contributions to sustainable development in the IW sense, we compare country-specific CWB with the corresponding welfare measure of country-specific manufactured capital (K) wealth investments (KWI), that is, the present value, in consumption equivalents, of all historical investments in manufactured capital.

Global CWB relative to global gross KWI is 0.52% (95% CI ±0.02%) and 3.71% (95% CI ±0.14%), and relative to net investment, 0.91% (95% CI ±0.03%) and 6.95% (95% CI ±0.26%), for the calibrated and the expert-based SDR (Fig. 3a,b, respectively). The 20 countries with the largest cumulative emissions differ substantially. The United States, China and India exceed the global ratio (gross and net), while several European countries with large emissions in the past are below the global ratio of CWB to KWI. In particular France and Italy have rather low CWB relative to their capital investments; their CBW relative to net KWI is

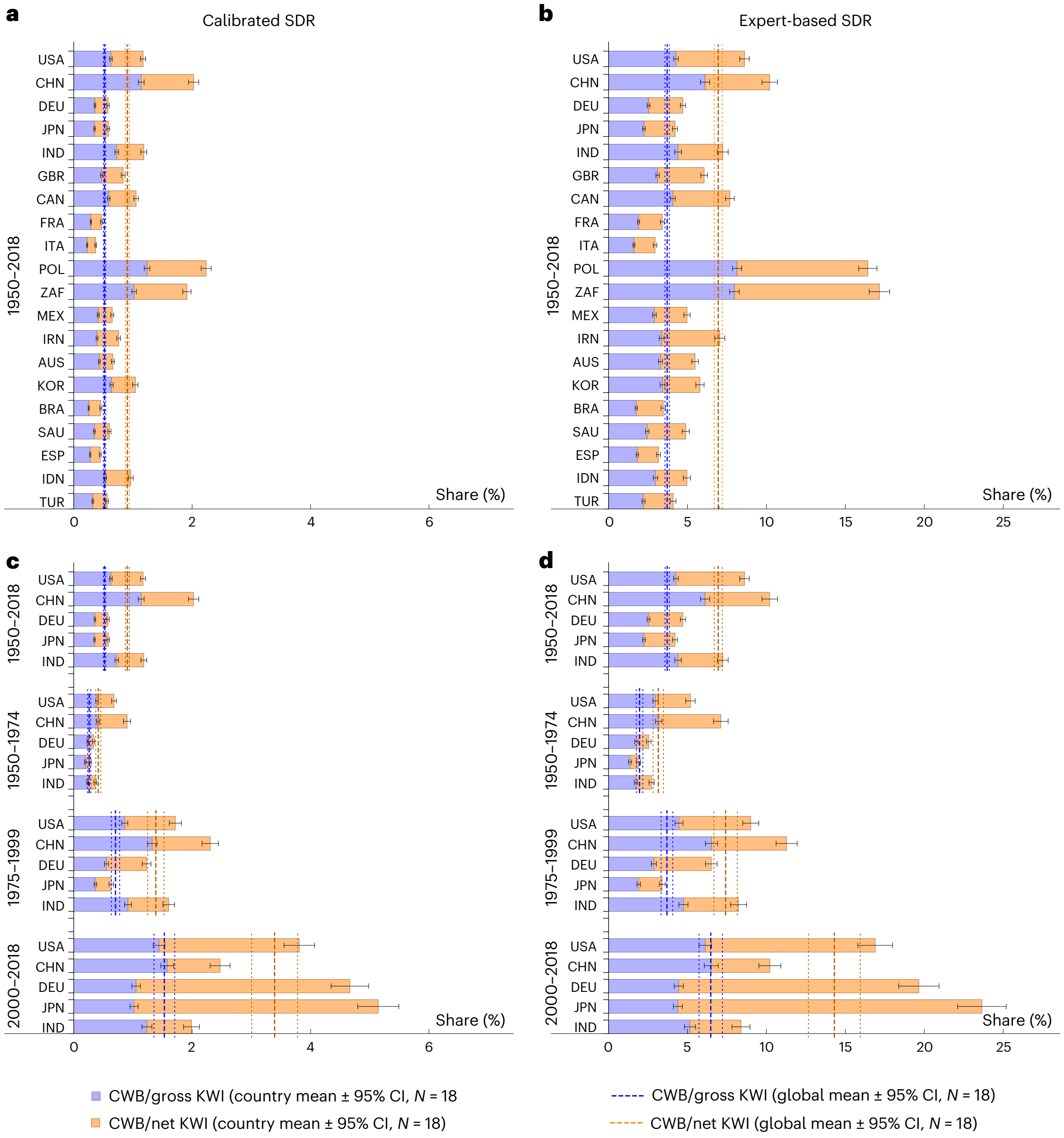

Fig. 3 | CWB relative to manufactured capital wealth investments (KWI). **a**,**b**, Mean CWB relative to gross and net KWI and 95% CIs, based on the time period from 1950 to 2018, for global CWB (dashed lines) and for the largest 20 countries in terms of cumulative CO_2 emissions. As for Russia, Ukraine and Kazakhstan investment time series do not start before 1990, these countries are omitted. **c**,**d**, Mean CWB relative to gross and net KWI and 95% CIs, for the entire period from 1950 to 2018, and for the three periods, 1950–1974, 1975–1999 and 2000–2018, for global CWB (dashed lines) and for the five largest countries terms of cumulative CO_2 emissions (excluding Russia). USA, the United States; CHN, China; DEU, Germany; JPN, Japan; IND, India; GBR, the United Kingdom; CAN, Canada; FRA, France; ITA, Italy; POL, Poland; ZAF, South Africa; MEX, Mexico; IRN, Iran; AUS, Australia, KOR, South Korea; BRA, Brazil; SAU, Saudi Arabia; ESP, Spain; IDN, Indonesia; TUR, Turkey.

even lower than the global ratio of CWB to gross KWI. It is the other way around for Poland and South Africa. Results for all countries are presented in Supplementary Table 1.

Applying the calibrated SDR results in a considerable smaller ratio (globally and across countries) not only because CWB is considerably lower (see above) but also because the rather high SDR implies a stronger compounding effect for investments in manufactured capital. Accordingly, periods with still rather low emissions, but high capital investments, like in the 50s and 60s have a higher weight in the aggregated figures. In turn, countries differ in their deviation from the global ratio of CWB to KWI across the two SDRs, depending also on the time profile of their CO_2 emissions and manufactured capital investments.

The time profile of CWB relative to (gross and net) KWI for the five countries with the largest cumulative emissions (excluding Russia) indicates different trends for CWB/KWI over time (for the calibrated and expert-based SDR, Fig. 3c,d, respectively). While China had the highest CWB relative to its (gross and net) KWI in the early periods 1950–1974 and 1975–1999, this changed in the more recent past, if considering net investments. In the period 2000–2018, Japan, Germany and the United States had a higher CWB relative to KWI for both SDRs than China and China's share even dropped below the global mean CWI/net KWI share. Hence, China's more recent increase in CO_2 emissions was less than proportional to its increase in investment. A similar development can be seen for India. On the other hand, 'old' industrial countries like Japan, Germany and the United States increased their CWB relative to gross and net KWI. While in the period 2000–2018, Japan's and Germany's CWB relative to gross KWI is still below the corresponding global value, this is not the case when considering net investments. This indicates that these countries have been investing a lot to maintain their manufactured capital basis, but were not able to sufficiently decarbonize their capital stock and production, showing an increasing challenge for sustainable development.

Discussion

Results on CWB are sensitive to the SDR applied. Calibrating the model to historical data leads to an SDR of 6.75% per year, which is higher than the SDR of 4.35% per year assumed by Nordhaus[4]. We contrast results for the calibrated SDR to an alternative, lower SDR that assigns higher weight to future climate impacts. The substantial differences of the SCC—both in current values at the year of emissions and in present values in 2018—for the two SDF are clearly visible in Fig. 1. Especially, the higher SDR assigns relatively more weight to past emissions, that is, the period where industrialized countries in Europe and the United States emitted already a substantial amount of CO_2. The aggregated results show that the level of the SCC (that is accounting for climate impacts) dominates the compounding effect and, in turn, the lower SDR translates into higher CWB absolutely and also as share of manufactured capital investment. However, using the low, expert-based SDR leads to results inconsistent with the historical observations on investments in manufactured capital.

Results on CWB also strongly depend on the quantification of the economic impacts of climate change, which still are highly uncertain[16,22,23]. We contrast a rather shallow impact function provided by Nordhaus[4] and a rather steep impact function, provided by Howard and Sterner[19], complemented by a (for low temperature increases) modest impact function provided by Weitzman[18]. The uncertainty in economic climate impacts translates into large CIs for the mean SCC. For the Nordhaus-only impact function, the mean SCC in 2018 are 8.33 (95% CI ±0.43) and 33.14 (95% CI ±3.76) USD/tCO_2 and for the Howard–Sterner-only impact function, the mean SCC in 2018 are 26.56 (95% CI ±1.45) and 99.04 (95% CI ±11.20) USD/tCO_2, for the calibrated and expert-based SDR, respectively. Considering only the impact function provided by Howard and Sterner[19] and the expert-based SDR, mean global CWB increases from 87.92 (95% CI ±3.23) to 150.57 (95% CI ±1.94) trillion USD (in 2017 PPP prices) and the share of CWB relative to the present value of manufactured capital investments increases from 3.71% (95% CI ±0.13%) and 6.94% (95% CI ±0.26%) to 6.36% (95% CI ±0.08%) and 11.90% (95% CI ±0.15%), for the expert-based SDR, for gross and net investments, respectively.

The impact functions we consider account neither for potential climate impacts on economic growth nor for the uncertainty of climate-change impacts triggered, for example, by tipping points[24]. The former could increase climate impacts tenfold[16]. However, the empirical evidence for the (persistent) impact of climate change on economic growth is inconclusive, while the estimated impact on economic output levels is consistent with the impact estimates of major IAMs[25]. Uncertain climate impacts are a major argument for the guardrail approach to temperature targets as adopted in the Paris Agreement. However, it would be normatively challenging to justify the evaluation of historical emissions with a policy target that was not introduced before 2015, and in turn a budget approach does not allow deriving welfare implications of past CO_2 emissions. In contrast, the welfare-theoretic approach we propose here does allow such a derivation irrespective of the past or current climate policy framework due to the influence of past CO_2 emissions on wealth.

Our analysis is (1) restricted to country-specific fossil and industrial-process CO_2 emissions, (2) neglects the regionally uneven distribution of carbon sinks and (3) does not account for regional variation in climate change impacts. Due to (1) and (2), we probably underestimate CWB for countries with high agricultural emissions, whereas we overestimate the CWB for countries with large forest carbon sinks. Using consumption-based instead of territorial CO_2 emission would allow to account for the CWB implications arising from trade. Furthermore, (3) implies that we do not distinguish between domestic and abroad CWB of a country's CO_2 emissions and only derive global CWB. Such an analysis would require country-specific SCC[26]. However, since country-specific SCC are small relative to the (global) SCC[27], using the global SCC figure provides already a comprehensive quantification of CWB.

As the IW framework, also CWB is based on a weak sustainability concept, according to which CO_2 emissions can be compensated by investments in human-made capital stocks. Implications of climate change, in particular on various non-use values provided by natural capital stock, might favour an assessment under a concept of strong sustainability, which supposes limited substitution possibilities between capital stocks and/or investment in specific adaptation and restoration capital funds ([28] and[15], respectively). Focusing on cumulative CO_2 emissions can be seen as related to such a strong sustainability assessment of climate change. However, our analysis has shown that both perspectives lead to similar conclusions when comparing country-specific cumulative emissions and CWB because the compounding (reverse discounting) effect balances the increasing marginal damage effect.

Conclusions

Past CO_2 emissions, increasing atmospheric CO_2 concentration, have caused and will cause climate damage worldwide in the past, present and future, and reduce global IW. We propose the concept of CWB to quantify the present value of climate damages from past CO_2 emissions. From an IW perspective, CWB is the value of investments in human-made capital that is required to compensate for the wealth reductions from past and current CO_2 emissions, to achieve sustainable development. We quantify CWB for the period 1950–2018, showing also how these reductions in IW compare with investments in manufactured capital. The latter allows assessment of the implications of CWB on sustainable development under a concept of weak sustainability, that is, considering the shadow-price aggregated change in capital stock. Still, the comparison of CWB with investments into manufactured capital indicates to which extent the cost countries impose on the global society by their CO_2 emissions is accompanied with a strong increase in private, country-specific wealth. In turn, different fairness principles such as the polluter-pays or ability-to-pay principle would result in different responsibilities and potential financial burdens for climate change mitigation and adaption[29]. The concept of CWB and the methods developed here provide a quantitative basis to apply the different fairness principles. Furthermore, we show that the SDR influences the CWB not only by deflating future impacts but also by compounding past cost. A high SDR assigns a relatively larger responsibility to past emissions and hence to industrialized countries. However, we show that the two effects roughly offset each other. As a consequence, approximating CWB by applying constant, current SCC provides fairly accurate estimates. Accordingly, while in contrast to a CO_2 budget approach, a welfare-theoretic perspective should account for the time profile of past CO_2 emissions, in quantitative terms both approaches lead to similar results.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01709-1.

References

1. Fenichel, E. P. et al. Wealth reallocation and sustainability under climate change. *Nat. Clim. Change* **6**, 237–244 (2016).
2. Friedlingstein, P. et al. Global carbon budget 2020. *Earth Syst. Sci. Data* **12**, 3269–3340 (2020).
3. Allen, M. R. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166 (2009).
4. Nordhaus, W. D. Revisiting the social cost of carbon. *Proc. Natl Acad. Sci. USA* **114**, 1518–1523 (2017).
5. Dietz, S. & Venmans, F. Cumulative carbon emissions and economic policy: in search of general principles. *J. Environ. Econ. Manag.* **96**, 108–129 (2019).
6. IPCC *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, 2021).
7. Arrow, K. J., Dasgupta, P. & Ma ler, K.-G. Evaluating projects and assessing sustainable development in imperfect economies. *Environ. Resour. Econ.* **26**, 647–685 (2003).
8. Fenichel, E. P. et al. Measuring the value of groundwater and other forms of natural capital. *Proc. Natl Acad. Sci. USA* **113**, 2382–2387 (2016).
9. Fenichel, E. P. et al. Wealth reallocation and sustainability under climate change. *Nat. Clim. Change* **6**, 237–244 (2016).
10. UNU-IHDP & UNEP. *Inclusive Wealth Report 2012. Measuring Progress Toward Sustainability* (Cambridge Univ. Press, 2014).
11. UNU-IHDP & UNEP. *Inclusive Wealth Report 2014. Measuring Progress Toward Sustainability* (Cambridge Univ. Press, 2014).
12. Managi, S. & Kumar, P. *Inclusive Wealth Report 2018. Measuring Progress Toward Sustainability* (Routledge, 2018).
13. The White House. National strategy to develop statistics for environmental-economic decisions: a U.S. system of natural capital accounting and associated environmental-economic statistics. Tech. Rep. Document ID 2022-17993. *Office of Science and Technology Policy, Office of Management and Budget, Department of Commerce, The White House* https://www.whitehouse.gov/wp-content/uploads/2022/08/Natural-Capital-Accounting-Strategy.pdf (2022).
14. Maher, S. M., Fenichel, E. P., Schmitz, O. J. & Adamowicz, W. L. The economics of conservation debt: a natural capital approach to revealed valuation of ecological dynamics. *Ecol. Appl.* **30**, e02132 (2020).
15. Bastien-Olvera, B. A. & Moore, F. C. Use and non-use value of nature and the social cost of carbon. *Nat. Sustain.* **4**, 101–108 (2021).
16. Tol, R. S. J. The economic impacts of climate change. *Rev. Environ. Econ. Policy* **12**, 4–25 (2018).
17. Arrow, K. J., Dasgupta, P., Goulder, L. H., Mumford, K. J. & Oleson, K. Sustainability and the measurement of wealth. *Environ. Dev. Econ.* **17**, 317–353 (2012).
18. Weitzman, M. L. GHG targets as insurance against catastrophic climate damages. *J. Public Econ. Theory* **14**, 221–244 (2012).
19. Howard, P. H. & Sterner, T. Few and not so far between: a meta-analysis of climate damage estimates. *Environ. Resour. Econ.* **68**, 197–225 (2017).
20. Hänsel, M. C. et al. Climate economics support for the UN climate targets. *Nat. Clim. Change* **10**, 781–789 (2020).
21. Drupp, M. A., Freeman, M. C., Groom, B. & Nesje, F. Discounting disentangled. *Am. Econ. J. Econ. Policy* **10**, 109–34 (2018).
22. Rennert, K. et al. Comprehensive evidence implies a higher social cost of CO_2. *Nature* **610**, 687–692 (2022).
23. Tol, R. S. J. A meta-analysis of the total economic impact of climate change. Preprint at *SSRN* https://doi.org/10.2139/ssrn.4443398(2023).
24. Dietz, S., Rising, J., Stoerk, T. & Wagner, G. Economic impacts of tipping points in the climate system. *Proc. Natl Acad. Sci. USA* **118**, e2103081118 (2021).
25. Newell, R. G., Prest, B. C. & Sexton, S. E. The GDP–temperature relationship: implications for climate change damages. *J. Environ. Econ. Manag.* **108**, 102445 (2021).
26. Bertram, C. et al. The blue carbon wealth of nations. *Nat. Clim. Change* https://doi.org/10.1038/s41558-021-01089-4 (2021).
27. Tol, R. S. A social cost of carbon for (almost) every country. *Energy Econ.* **83**, 555–566 (2019).
28. Rickels, W., Quaas, M. F. & Visbeck, M. How healthy is the human–ocean system? *Environ. Res. Lett.* **9**, 044013 (2014).
29. Baatz, C. Responsibility for the past? Some thoughts on compensating those vulnerable to climate change in developing countries. *Ethics Policy Environ.* **16**, 94–110 (2013).

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Methods

CWB

Our CWB approach builds on the discounted Utilitarian framework, which is standard in the climate economics literature[30]. We define the CWB by a country with emission path $\mathbf{e} = (e_{1950}, e_{1951}, \ldots, e_{2018})$ as the present global wealth, measured in consumption equivalents at point in time $t = 2018$, that compensates for the climate damages caused by $\mathbf{e}$. $\text{CWB} \equiv \Delta C_{2018} = \sum_{t=1950}^{2018} \text{SCC}_{2018,t} \cdot e_t$. CWB is computed from the present values SCC_{2018} of past emissions, which are derived as: $\text{SCC}_{2018,t} = \frac{\partial W/\partial E_t}{\partial W/\partial C_{2018}}$, where W denotes total welfare, and e_t, and C_t denote CO_2 emissions and total consumption in year t, respectively, that is, the SCCs and CWB are measured in terms of consumption. We relate CWB to past investments in manufactured capital, which in contrast to CO_2 emissions increase wealth. We distinguish between gross investments and net investments, the latter accounting for capital depreciation. The former is informative in terms of indicating a country's savings, that is, directing output to wealth-increasing activities. The latter indicates whether investments are sufficient to at least maintain its capital base. As for CWB, we use a welfare measure, abbreviated KWI for capital (K) wealth investments, which captures the present value of all past investments in manufactured capital, and express the value of past investments in consumption equivalents in the year 2018. KWI is derived as the compensating surplus, in 2018 and with respect to global welfare, for the stream of investments that one country adds to the global economy. The present value equivalent surplus for the stream of investments 1950–2018 is $\Delta C_{2018} = \sum_{t=1950}^{2018} \Delta C_{2018,t} = \sum_{t=1950}^{2018} \frac{(1+\delta)^{-T} U'(c_T)}{(1+\delta)^{-2018} U'(c_{2018})} I_t$, which can be equivalently expressed as $\Delta C_{2018} = \sum_{t=1950}^{2018} \frac{\partial W/\partial C_t}{\partial W/\partial C_{2018}} I_t$. The formal derivation of CWB and KWI is detailed in Section 2 in Supplementary Information B.

IAM and calibration

We calibrate a global IAM based on DICE[4] to quantify the SCC_t time series. The IAM allows maximizing of welfare W, that is, the present value of aggregate utility $L_t\,U(c_t)$, which derives from the world population of size L_t and the level of per-capita consumption c_t, by determining the optimal paths for CO_2 emissions abatement and capital investment. However, the model also allows one to derive the shadow price information for given, that is, non-optimal, emissions abatement and capital investment paths. Unabated CO_2 emissions from the production process increase atmospheric CO_2 concentration and, in turn, global mean temperature, which reduces output (climate damages). The model structure is detailed in Section 3 in Supplementary Information B.

The IAM is calibrated to match observed global economic figures (output, capital stock, investment, depreciation and output elasticity of capital) from the Penn World Tables[31] and to match observed, global fossil fuel and industrial CO_2 emission from the Global Carbon Project[2]. The underlying deterministic economic growth framework of the IAM is not capable of reproducing business cycles in individual countries[32], though can be calibrated so that global aggregated and therefore smooth output and investment time series are matched. The derived SCC and (global) consumption discount rate obtained from the model are then applied to derive the country-specific results.

Following Nordhaus[4], we measure economic variables in PPP where our units are 2017 US$ (international dollars). Both capital stock and investments are denoted in output PPP since the conversion of capital data into PPP currencies uses a different PPP exchange rate than used for output in the Penn World Tables. For the investment time series, we use initial capital stocks in 1950 and calculate then a gross and net investment time series by using 'share of gross capital formation at current PPPs' and the depreciation rates, both obtained from the Penn World Tables. The calibration of economic output is detailed in Section 4.1 in Supplementary Information B. We replace the DICE carbon cycle and climate dynamics by the climate and carbon cycle model Finite Amplitude Impulse Response (FaIR)[33] and the energy-balance model provided by Geoffroy et al.[34] which have been shown to replicate historic CO_2 concentration time paths and corresponding global mean temperature increase accurately[35–37]. The calibration of the carbon cycle and climate system is detailed in Section 4.2 in Supplementary Information B. As discussed in the main text, we consider three different climate damage functions, Nordhaus[4], Weitzman[18], and Howard and Sterner[19]. The damage functions and calibration of the abatement cost function are detailed in Section 4.3 in Supplementary Information B.

Until the year 2018 we impose the observed paths for investment and CO_2 emissions abatement and derive optimal policies thereafter. Following Nordhaus[4] we assume that certain properties such as population growth and development of non-CO_2 forcing are exogenous and consider in addition to the baseline DICE specification, five further scenarios based on the baseline shared socio-economic pathways specification[38]. Accordingly, we consider in total 18 scenarios, that is, six scenarios for the three climate damage functions each. Accordingly, the presented results display if not indicated otherwise the mean over the 18 scenarios and 95% CI, implying that each climate impact function is assigned the same weight. The selection and calibration of the exogenous parameters are detailed in Section 4.4 in Supplementary Information B.

Discounting

We use two different model specifications with respect to discounting. In the first specification, we calibrate the parameters determining the SDR, the pure rate of time preference (δ) and the marginal elasticity of utility (η), to match the historical path of investment from 1950 until 2018 under optimal investment. We find that the observed path for the global capital stock is matched for combinations of δ and η that satisfy $\eta = 3.268 - 0.47 \cdot \delta$ (in % per year). Numerically, the closest fit with the observed capital stock in the year 2019 is obtained with $\delta = 4.4\%$ per year and $\eta = 1.2$. This calibration results in an SDR of 6.75% for that period. The second specification uses an expert-based parameterization from the survey by Drupp et al.[21] with $\delta = 1.1\%$ per year and $\eta = 1.35$, which translates into an SDR of 3.74% for that period. Note that a lower SDR would result in higher capital stocks in 2019 as the observed capital stocks if the IAM is optimized starting in 1950 since a lower SDR implies higher present value returns from capital investment and therefore less consumption. However, under both specifications we derive the SCC under given, that is, observed, levels of capital investment and CO_2 emissions. The calibration of the SDR is detailed in Section 4.5 in Supplementary Information B.

Data availability

The authors declare that the data on the calibration of the IAM is included in the GitHub repository https://github.com/femeier/Historic-DICE.

Code availability

The authors declare that the code of the IAM, the calibration file and the code for the IW assessment are included, accompanied with a detailed instruction are in the GitHub repository https://github.com/femeier/Historic-DICE.

References

30. Stern, N. *The Economics of Climate Change—The Stern Review* (Cambridge Univ. Press, 2007).
31. Feenstra, R. C., Inklar, R. & Timmer, M. P. The next generation of the Penn World Table. *Am. Econ. Rev.* **105**, 3150–3182 (2015).
32. Millner, A. & McDermott, T. K. Model confirmation in climate economics. *Proc. Natl Acad. Sci. USA* **113**, 8675–8680 (2016).

33. Smith, C. J. et al. Fair v1.3: a simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* **11**, 2273–2297 (2018).
34. Geoffroy, O. et al. Transient climate response in a two-layer energy-balance model. Part I: analytical solution and parameter calibration using CMIP5 AOGCM experiments. *J. Clim.* **26**, 1841–1857 (2013).
35. Rickels, W. & Schwinger, J. Implications of temperature overshoot dynamics for climate and carbon dioxide removal policies in the dice model. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/ac22c0 (2021).
36. Dietz, S., van der Ploeg, F., Rezai, A. & Venmans, F. Are economists getting climate dynamics right and does it matter? *J. Assoc. Environ. Resour. Econ.* **8**, 895–921 (2021).
37. Azar, C. & Johansson, D. J. A. Dice and the carbon budget for ambitious climate targets. *Earth's Future* **9**, e2021EF002041 (2021).
38. Riahi, K. et al. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* **42**, 153–168 (2017).

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Author contributions

W.R. had the initial idea for the study and developed the concept together with M.Q. W.R., F.M. and M.Q. conceived and designed the assessment of historical CO_2 emissions, performed the calculations, analysed the data, contributed material and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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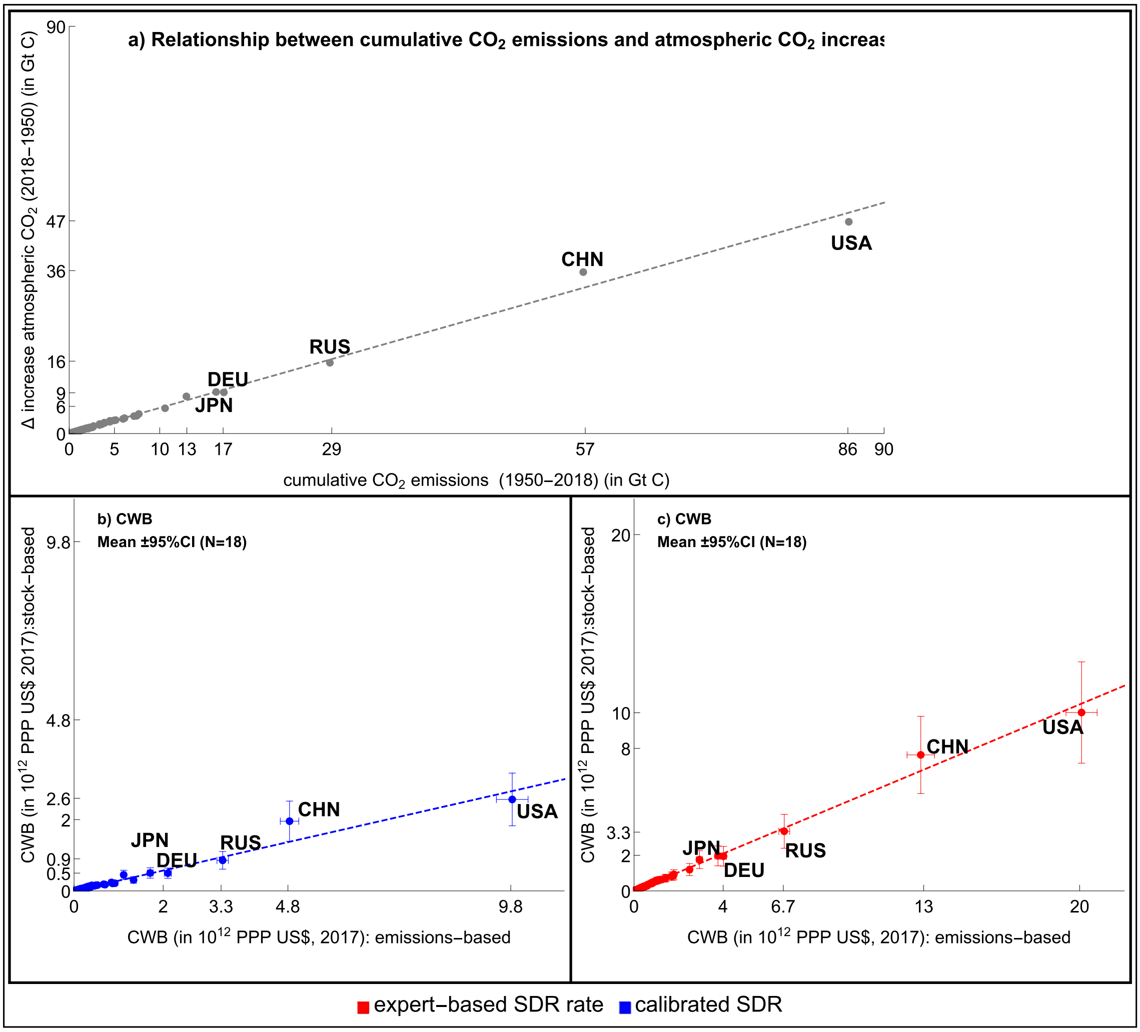
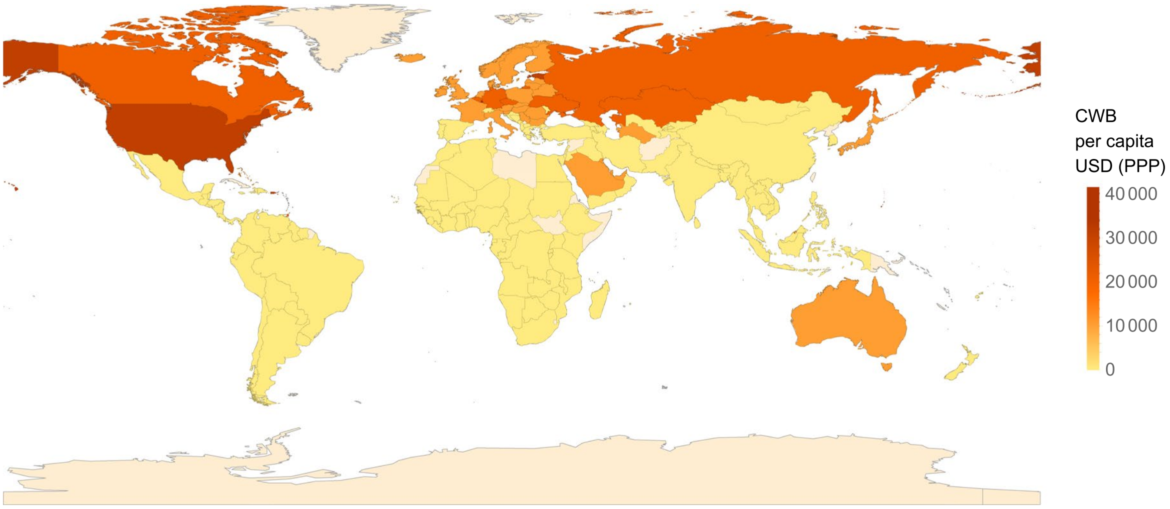


Extended Data Fig. 1 | Emissions-based versus Stock-based CWB Assessment. Panel a shows the relationship between cumulative energy- and industrial CO_2 emissions and the corresponding fraction in the atmosphere. The latter has been calculated using the climate carbon cycle FaIR-Geoffroy model[33,34] by excluding for each country under investigation its energy-related and industrial process emissions from the emissions paths. The corresponding share in the atmosphere is then obtained from the difference in atmospheric CO_2 concentration in 2019 between the run with emissions of all countries and the run with the country under consideration excluded. Panel b and c show the relationship between emissions-based and stock-based CWB for the calibrated- and expert-based social discount rate, respectively. The stock-based CWB is obtained by multiplying the attributed atmospheric carbon stock of the country under consideration with the social cost of carbon in 2018. The error fences show the 95% confidence intervals of the mean (N=18). The dashed lines show in all three panes a linear model fit. USA, The United States; CHN, China; RUS, Russia; DEU, Germany; JPN, Japan.



Extended Data Fig. 2 | Mean per capita CWB for the calibrated SDR. The figure has been created using Wolfram Research, Inc., Wolfram|Alpha Knowledgebase, Champaign, IL (2021).