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Use and non-use value of nature and the social cost of carbon

Bernardo A. Bastien-Olvera [1]✉ and Frances C. Moore [2]

Climate change is damaging ecosystems throughout the world with serious implications for human well-being. Quantifying the benefits of reducing emissions requires understanding these costs, but the unique and non-market nature of many goods provided by natural systems makes them difficult to value. Detailed representation of ecological damages in models used to calculate the costs of greenhouse gas emissions has been largely lacking. Here, we have expanded a cost–benefit integrated assessment model to include natural capital as a form of wealth. This brings benefits to people through non-use existence value and as an input into the production of ecosystem services and market goods. In our model, using central estimates for all parameters, optimal emissions reach zero by the year 2050, limiting warming to 1.5 °C by the year 2100. We used Monte Carlo analysis to examine the influence of several key uncertain model parameters, and examined the effect of adaptive investments in natural systems that partially offset climate damages. Overall, we show that accounting for the use and non-use value of nature has large implications for climate policy. Our analysis suggests that better understanding climate impacts on natural systems and associated welfare effects should be a high priority for future research.

Humans derive value from nature in multiple ways[1], which can be broadly categorized into use and non-use values[2,3]. Use values arise from the input of natural systems into economic activity, such as the flood-protection benefit mangroves provide to coastal cities or the raw materials used in producing market goods[4]. Non-use values instead arise directly from the existence of natural systems and species even in the absence of any direct use or consumption. Principal non-use values are existence value (knowledge that certain species or ecosystems exist) and bequest value (the ability of future generations to derive welfare from natural systems)[3,5].

Climate change is already having a discernible influence on ecosystem functioning, an effect that will continue to grow throughout the twenty-first century[6–12]. These changes will affect human well-being both through the disruption of ecosystem services and the direct and permanent loss of non-use value from extinctions and ecosystem degradation[13,14]. The unique characteristics of some benefits derived from ecosystems make them only imperfectly substitutable with other forms of consumption that contribute to welfare[15], and previous work has suggested that accounting for this imperfect substitutability may substantially increase estimates of the welfare costs of climate change[16–20]. In addition, any damage to the stock of natural capital would permanently reduce the flow of benefits from natural systems, meaning that costs arising from the ecological effects of climate change would be long-lived and cumulative[21].

Cost–benefit integrated assessment models represent interactions between the economy and climate, capturing trade-offs between the costs of reducing greenhouse gas emissions and the benefits of avoided climate change. These models calculate the social cost of carbon (SCC), an estimate of the net present value of a marginal ton of CO_2 emissions used in the cost–benefit analysis of climate and energy policy. The SCC should include a comprehensive accounting of impacts, including both effects on market sectors (which can be largely captured by standard economic indicators, such as gross domestic product (GDP)) as well as extra-market damages, such as changes to mortality and effects on natural systems[22,23]. Standard estimates of the SCC, however, include only a rough accounting of ecological damages and do not model either the imperfect substitutability of natural capital and ecosystem services or the potentially permanent loss of welfare associated with damages to the stock of natural capital[23]. These estimates may, therefore, be missing characteristics essential for assessing the welfare costs of anthropogenic climate change, something that was noted decades ago[24] but has not been widely implemented in the cost–benefit analysis of climate policy.

In this study we expanded the 2013R version of the Dynamic Integrated model of Climate and the Economy (DICE)[25] to represent the unique nature of climate change impacts on natural systems. In particular, we adopt the concept of comprehensive wealth widely developed in the sustainability literature[26–28], which includes natural capital as an input to production[28] in addition to the more standard manufactured capital and human capital. We modelled three pathways by which the stock of natural capital supports human welfare (Fig. 1):

- As a relatively minor input to the production of most market goods (orange arrows, Fig. 1)
- As a more important input to the production of ecosystem goods and services (green arrows, Fig. 1)
- As the source of non-use goods associated with existence and bequest values (blue arrows, Fig. 1)

We modelled the imperfect substitutability of these three types of goods in the social welfare function using a nested constant elasticity of substitution (CES) utility function. This functional form allows the two types of use-value outputs (economic output and ecosystem services) to be relatively close substitutes compared with the substitutability between non-use value and the bundle of use values (Methods). Additionally, we added a damage function that allows climate change to affect the stock of natural capital

[1]Geography Graduate Group, University of California Davis, Davis, CA, USA. [2]Environmental Science and Policy Department, University of California Davis, Davis, CA, USA. ✉e-mail: bastien@ucdavis.edu

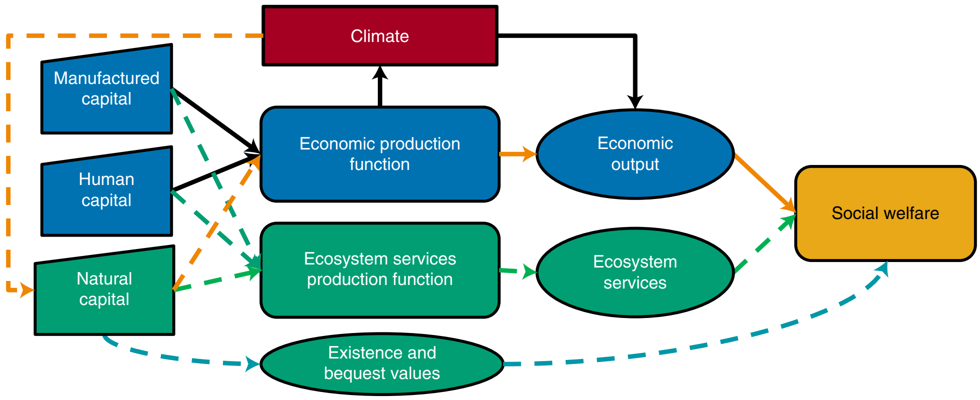

Fig. 1 | GreenDICE diagram for modelling the welfare effects of climate change impacts on natural capital. Schematic of the GreenDICE structure showing the instrumental (green and orange arrows) and intrinsic (blue arrows) pathways through which natural capital affects welfare. Dashed links represent additions to the standard DICE model. Solid black lines show relationships already present in DICE.

directly. We call this model with modified capital, production, utility and damages the GreenDICE model. Detailed equations and calibration parameters relevant to GreeenDICE are given in the Methods section.

We present here versions of the full GreenDICE model that gradually add these pathways to the standard DICE model in order to attribute damages to specific pathways. The first change to DICE involves including natural capital in the economic production function, allowing it to influence social welfare through the consumption of market goods. We call this the 'Market Only' specification (orange arrows, Fig. 1). The next specification is a complete representation of use values, where the production of ecosystem services is captured using a second production function that relies more heavily on natural than manufactured capital. Ecosystem services also enter into the utility function, contributing to welfare in a way that is only imperfectly substitutable with standard market goods. We call this the 'All Use Values' specification (orange and green arrows, Fig. 1). Finally, the complete specification also includes non-use values that arise directly from the natural capital stock and are again imperfectly substitutable with the bundle of use values, becoming a nested CES utility function. The full model, which includes all use and non-use values, is referred to simply as 'GreenDICE' (orange, green and blue arrows, Fig. 1).

Although previous work has revealed the importance of substitutability between environmental goods, broadly defined, and manufactured goods[17–19], a key advance here is in explicitly modelling the production of these goods from natural capital stock, including the potential for climate damages to affect this stock. This allows the possibility to distinguish between two primary pathways by which changes in natural capital affect welfare: those that operate through production, affecting use values, and those that arise directly from changes in the natural capital stock, affecting non-use values. This also distinguishes this model from previous work that incorporated natural capital into DICE[29], in which the costs of ecosystem degradation due to both climate and non-climate factors were modelled, but not the direct role of natural capital in production or the imperfectly substitutable nature of environmental goods. A final important distinction from previous work relates to the dynamics of damages. By explicitly modelling damages to the natural capital stock, the model allows impacts to be persistent and cumulative, because losses to natural capital can affect welfare in future time periods. Persistence is an important but poorly constrained determinant of total climate damages, and this modelling framework relaxes some of the constraints of the standard DICE model, in which damages only affect output and are therefore mostly non-persistent[21,30].

One important note is that ecosystem services should be understood here to exclude the carbon sequestration value of natural systems. Although this is an important component of ecosystem services, it should be represented explicitly in the DICE model as part of the carbon cycle, because changes to the land or ocean carbon sink will affect the social cost of carbon by altering the relationship between emissions and temperature. As has been pointed out in previous work[31], the carbon cycle model in DICE is very simple, omitting any feedbacks or direct representation of the land carbon sink. Modifying the DICE carbon cycle model is beyond the scope of this paper, so we simply note that the interpretation of ecosystem services represented here excludes carbon sequestration and instead captures other use values, such as recreation and aesthetic enjoyment, nutrient cycling and the provision of other extra-market goods and services.

Results

Figure 2 shows the trajectories of emissions that maximize welfare in the model with their corresponding temperature rise and the optimal carbon tax (SCC under welfare-maximizing conditions). We ran the model under standard DICE specifications and with the different specifications of GreenDICE. The introduction of additional damage pathways resulting from damages to natural capital increases the costs of climate change, raising the optimal carbon tax in 2020 (Fig. 2a), lowering welfare-maximizing emissions (Fig. 2b), resulting in lower global temperatures throughout the twenty-first century (Fig. 2c). Damages to natural capital reduce economic production (Market Only specification) and have a large effect compared with the standard DICE specification, limiting the temperature increase to 2 °C by the end of the century. Incorporating the relatively more important role of natural capital in producing ecosystem goods and services (All Use Values specification) has an additional effect, raising the optimal carbon tax in 2020 to US$133 per ton CO_2 from US$72 in the Market Only specification.

Adding non-use values to the full GreenDICE model (GreenDICE specification, Fig. 2) further increases welfare losses arising from damages to the natural capital stock. These losses, only imperfectly substitutable with consumption goods, increase the optimal carbon tax in 2020 to US$160 per ton CO_2, more than five times higher than the standard DICE model (US$28 per ton in 2020). Emissions decline rapidly, reaching zero by 2050 and limiting warming to 1.5 °C by the end of the century.

Many of the parameters relating to production, utility and damages introduced into GreenDICE are both uncertain and extremely challenging to measure directly. This is particularly the case for

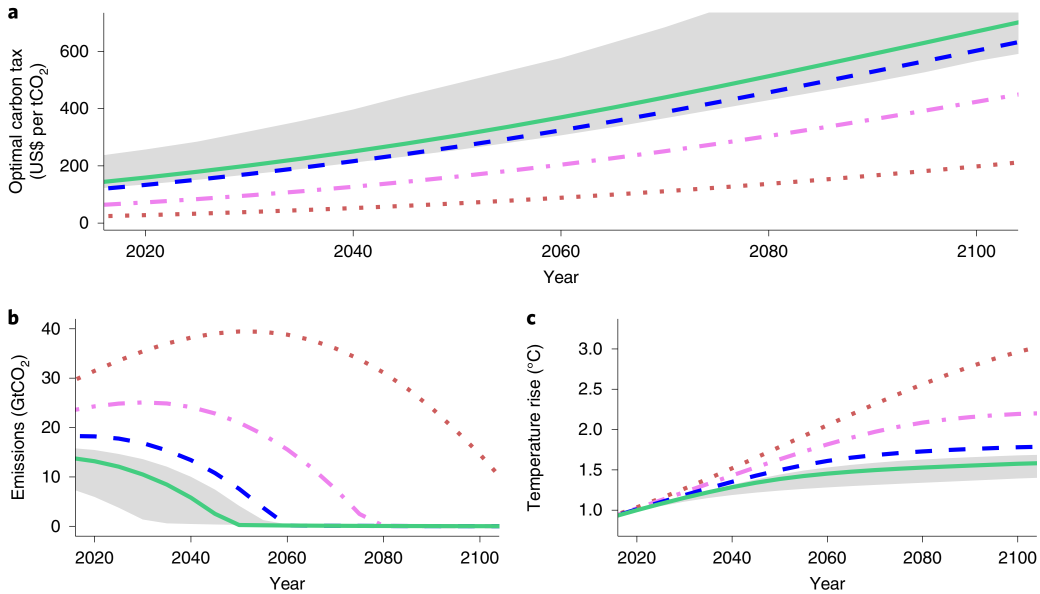

Fig. 2 | Climate policy results derived from the DICE and GreenDICE models. Key climate policy variables in the twenty-first century based on the standard DICE model (dotted line), Market Only specification of GreenDICE (dot-dashed line), All Use Values specification of GreenDICE (dashed line) and the complete specification of GreenDICE (solid line). The shaded areas show the interquartile spread of outcomes based on a Monte Carlo simulation of the eight parameters introduced into GreenDICE. **a–c**, The optimal carbon tax shown in US$$_{2019}$ per ton CO_2 (**a**), CO_2 emissions (**b**) and rise in global mean surface temperature above pre-industrial temperature (**c**).

the parameterization of non-use values in the utility function (through the parameters s_2 and γ_4, Supplementary Table 1), the magnitudes of which are debated within economics[32–34]. Moreover, there is no consensus on how to accurately measure these values, particularly at the high level of aggregation required to inform a model like GreenDICE. The values of these parameters are therefore not well supported empirically (Supplementary Table 1), so understanding their role in determining findings is important. We achieved this through an extensive exploration of the uncertain parameter space in both a one-at-a-time sensitivity analysis and a full Monte Carlo analysis.

We first performed a one-at-a-time sensitivity analysis of the full GreenDICE specification to compare the implications of uncertainty on key policy variables (details and uncertainty ranges are given in Supplementary Table 1). Figure 3 shows the effects of such parameters on the optimal carbon tax in 2020 and the global mean surface temperature in 2100 under welfare maximization conditions. The sensitivity to three widely studied parameters, the pure rate of time preference, the climate sensitivity and the relative risk aversion, are also provided for comparison.

Figure 3 shows the expected and well-understood sensitivity to the pure rate of time preference for values of 0.1, 1.5 and 3% (ref. [35]). Important policy variables are generally less sensitive to variation in the GreenDICE parameters. The three variables with the largest impact are the natural capital-adjusted total factor productivity (which partly determines the output elasticity with respect to natural capital; Supplementary Information), the elasticity of non-use values with respect to natural capital and the magnitude of climate change impacts on natural capital (damage to natural capital). If impacts to the natural system are larger than our central estimate or if natural capital plays a more important role in welfare than in our main specification, substantially more stringent climate policy could be warranted, including the stabilization of global temperatures well below 1.5 °C above pre-industrial temperatures. However, even given the uncertainty of key parameters, GreenDICE specifications consistently produce a larger optimal carbon tax in 2020 and, correspondingly, lower temperatures in 2100 than the standard DICE model (dashed line, Fig. 3).

The one-at-a-time sensitivity analysis might overlook important interactions among parameters. For example, a large role of natural capital in economic production combined with large damages to natural capital might imply much larger damages than from high values of either parameter alone. To shed light on these interaction effects, we performed a Monte Carlo analysis, sampling 1,000 times from all GreenDICE parameters and optimizing the model under the sampled parameters. To understand the factors and interactions driving variation in two key policy variables (the optimal carbon tax in 2020 and temperature in 2100), we fitted a random forest on the Monte Carlo analysis output[36]. This procedure creates 500 regression trees that sequentially partition the data to maximize the variance in the output variable explained by the partitions (Methods). The earlier in the regression tree a particular parameter appears, the more important it is in explaining the variation in policy variables from the Monte Carlo analysis[37].

Figure 4 shows the mean minimum depth for each variable in all 500 regression trees in the random forest. This clearly shows that the magnitude of climate change impacts on natural capital (damage to natural capital) has a dominating influence in determining the optimal carbon tax in 2020: it was always chosen as the first or second variable in the regression trees. Two other key variables are those that together determine the role of natural capital in production (natural capital-adjusted total factor productivity and the initial stock of natural capital; Supplementary Information). Additionally, the substitutability between welfare from use and non-use goods in the utility function proves important and has previously been identified as a critical parameter by other researchers in simpler models[17,19].

The interaction between important variables identified through the Monte Carlo analysis, namely the initial natural capital stock and the natural capital-adjusted total factor productivity, has been explored in more detail and the results are presented in Extended Data Fig. 1. The costs of ecological damages are much higher if the

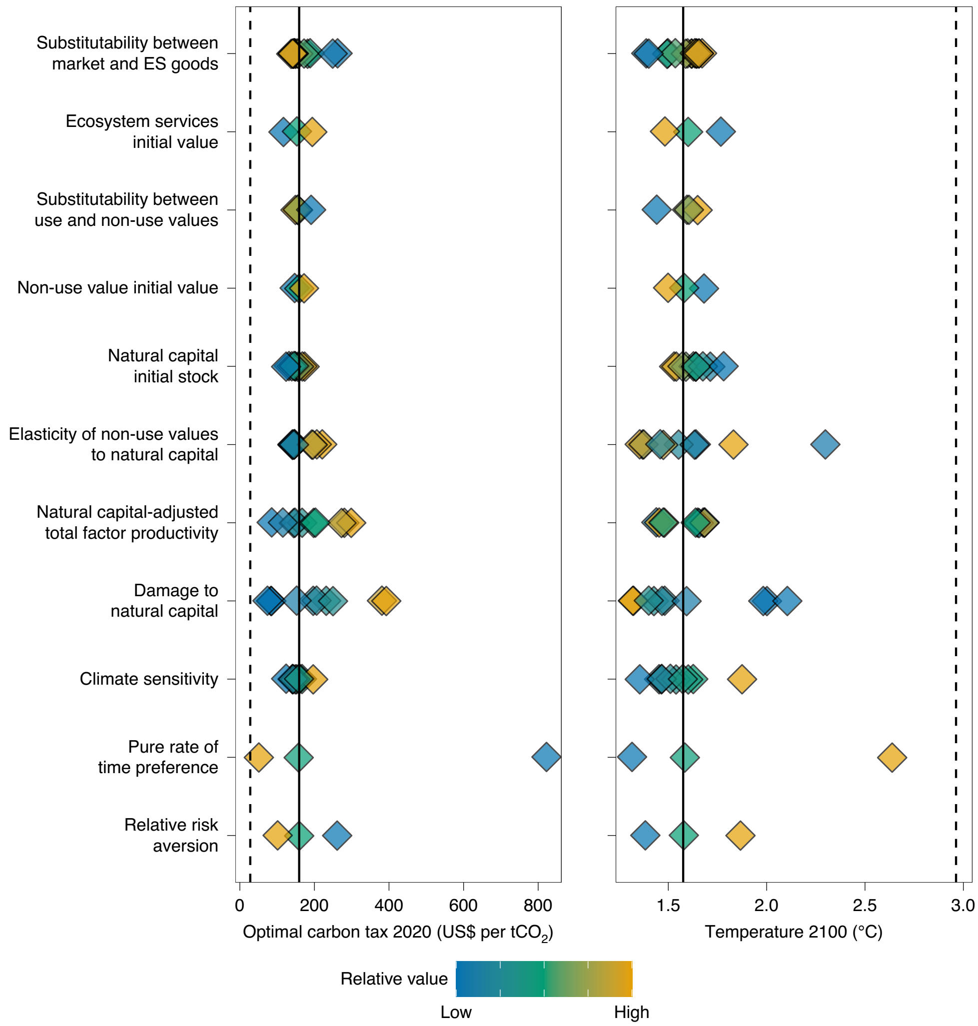

Fig. 3 | Sensitivity analysis of uncertain parameters under welfare maximization conditions. Sensitivity analysis of key uncertain parameters in GreenDICE. ES, ecosystem services. The colour gradient indicates the scaled parameter range between low (blue) and high (yellow) values. The vertical lines indicate the preferred GreenDICE (solid) and standard DICE (dashed) estimates. The [min,max] ranges of the values from top to bottom are as follows: θ_1: [−0.016,0.86]; s_1: [0.05,0.15]; θ_2: [0.27,0.78]; s_2: [0.05,0.15]; N_0:[$0.147K_0$, $0.912K_0$]; γ_4: [0.2,0.8]; atfp: [1.00065,1.043683]; a_n: [0,0.0806]; cs: [2.268,3.499]; prtp: [0.001,0.03]; α: [1.08,1.82]. More information on the parameters can be found in the Methods and the rationale for the ranges is provided in the Supplementary Information.

natural capital initial stock is large and plays an important role in production. Comprehensive wealth accounting in different countries shows that these conditions are most prevalent in developing economies. In particular, in poorer countries, natural capital tends to be large relative to both manufactured and human capital[28]. Thus, although GreenDICE does not explicitly model regional heterogeneity, results suggest that ecological damages may be disproportionately concentrated in developing countries.

It is important to note that both the Monte Carlo analysis and the sensitivity analysis explore the variation in model runs optimized given particular values of the uncertain parameters. The results, therefore, show the sensitivity of optimal mitigation pathways to different uncertain parameters. This is different from the single mitigation pathway that would be optimal given this uncertainty space, which has been explored in recent papers that implement dynamic stochastic versions of the DICE model that help to avoid potential policy inconsistencies[38–41]. The additional state variables in the GreenDICE model, as well as the large number of uncertain parameters, mean that a dynamic stochastic implementation is computationally challenging and beyond the scope of this paper. Therefore we simply note that the interpretation of uncertainty and optimal control explored here differs conceptually from that addressed in the growing literature on dynamic stochastic integrated assessment models.

Finally, we also explored the role of adaptive investments in alleviating the costs of ecological damages from climate change. In the standard DICE model, production can be invested either in capital for future production or in greenhouse gas mitigation, with the remainder contributing to utility through consumption. We added an additional savings pathway to GreenDICE, allowing production to also be used to offset the damages to natural capital from climate change (called the Adaptive Investments model). This is a highly stylized representation of adaptive spending for ecological systems that could include protection of habitat, managed relocation of species and increased conservation spending to prevent extinction. GreenDICE was re-optimized with this additional savings pathway as a third control variable. Calibration and details of implementation are given in the Methods section with the sensitivity to parameterizations of the cost function given in Extended Data Fig. 2.

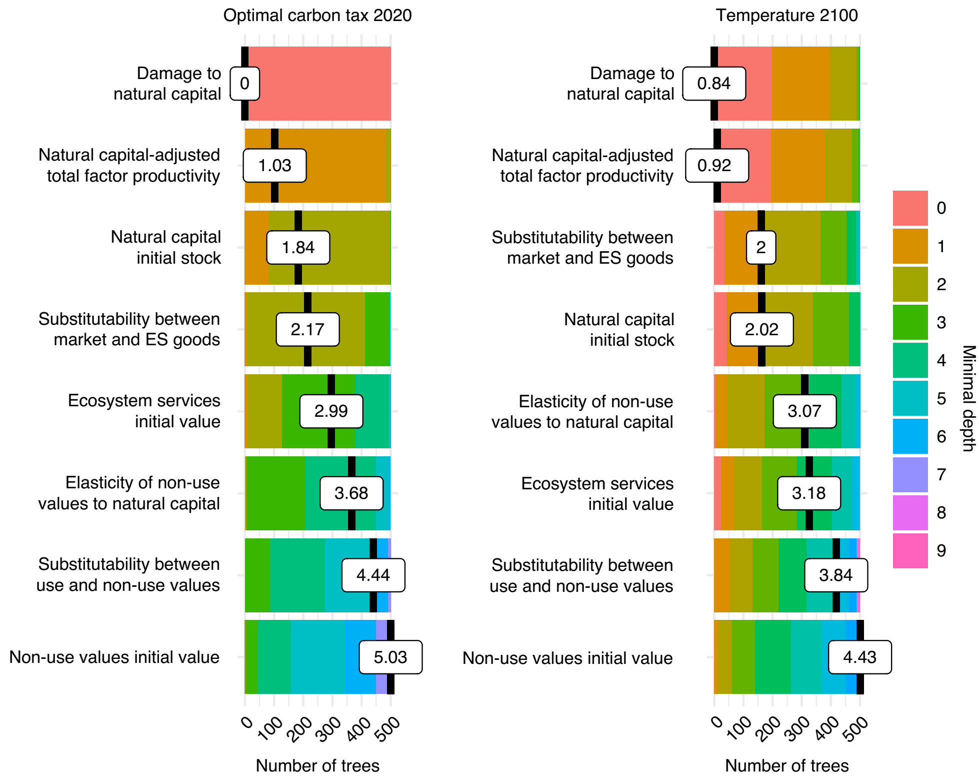

Fig. 4 | Random forest analysis of Monte Carlo simulation. Minimal depth at which each parameter is found in each tree of the random forest, predicting the social cost of carbon in 2020 (left) and temperature in 2100 (right) based on Monte Carlo simulations. A lower minimal depth indicates that the parameter has more importance in explaining variation in the variable of interest.

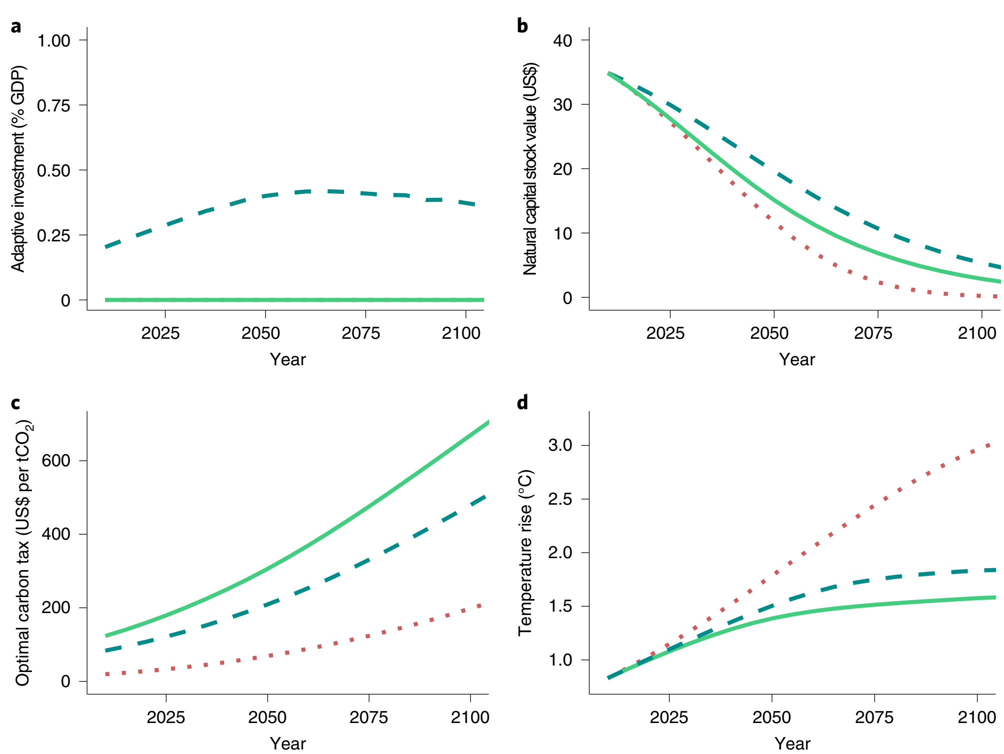

Fig. 5 | Impacts of the Adaptive Investments model on natural capital and climate damage. a–d, Effects of the Adaptive Investments model (dashed line) on investments in adaptation (**a**), natural capital stock (**b**), the optimal carbon tax (**c**) and rise in temperature (**d**) compared with the standard DICE model (dotted line) and GreenDICE (solid line) .

Figure 5 shows the results from implementing this additional savings pathway, comparing the investments in natural capital, natural capital stock, the optimal carbon tax and global temperatures with both DICE and GreenDICE. The Adaptive Investments model reduces temperature impacts and produces a constant stream of investments just above 0.25% of gross world product (GWP) throughout the century in the preferred parameterization of the cost function[42]. In the model, these investments are able to partially offset ecological climate damages, producing an optimal carbon tax lower than GreenDICE and allowing for a slightly higher temperature at the end of the century. This result points to the importance of adaptation in determining climate change damages, something emphasized in previous studies[43,44]. However, the question of how much protecting natural systems from climate change would cost and exactly how effective that spending would be at reducing the welfare costs of ecological impacts is highly uncertain.

Discussion

In Extended Data Fig. 3 we also show the results from an alternative implementation of savings that allows output to be invested directly in natural capital, in the same way that output is invested in manufactured capital in the standard DICE model. This is a highly aggregate representation of spending to restore, expand and improve natural systems, for instance, through the expansion of protected areas and managed restoration efforts not necessarily tied to climate change damages as in the Adaptive Investments implementation shown in Fig. 5.

Extended Data Fig. 3 shows that allowing this direct investment leads to very large initial investments in natural capital that greatly increase the existing natural capital stock. This behaviour suggests that the level of natural capital in GreenDICE is lower than that which would maximize welfare in the model, because relaxing the constraint on the level of natural capital produces much larger stocks. Parameterizations of the initial natural capital stock are taken from estimates from the literature on comprehensive wealth accounting (Methods), suggesting either that the importance of natural capital in utility is over-estimated in GreenDICE or that current stocks of natural capital are far below optimal levels. Given that many of the benefits provided by ecosystems are public goods, which are notoriously difficult to provide optimally, it would not be surprising if natural capital today were, in fact, lower than welfare-maximizing levels. However, we note that this modelling abstracts away from real dynamic constraints that limit the rate at which economic output can be converted into natural capital, and these results should therefore be understood as illustrative only.

Natural systems support human welfare through a variety of pathways. Because these systems are thought to be particularly vulnerable to climate change impacts, and because natural capital and the goods it provides are only partially substitutable with either other forms of capital or other consumption goods, explicitly modelling the macroeconomic role of natural capital is important to accurately estimate the effects of climate change on human well-being. Failing to acknowledge nature's unique contributions to social welfare through use and non-use values, and the threats posed by climate change to natural systems, risks substantially underestimating the costs of climate change.

Parameterization of GreenDICE has been informed by a number of existing studies estimating the importance of natural capital in economic production (Methods and Supplementary Table 1). However, both the magnitude and uncertainty of impacts demonstrated here point to the need for more work to improve the precision of these parameter estimates. The GreenDICE parameter identified as the most important in the Monte Carlo analysis was the damage function parameter that relates changes in climate to impacts on natural systems (Fig. 4). Therefore, integrating current knowledge from ecology on the risks climate change poses to the provision of ecosystem services and biodiversity[45] could substantially improve confidence in the effects reported here, although gaps in the scientific understanding of the response of natural systems to climate change, including potential thresholds and tipping points, remain.

In addition, versions of the model that allow for adaptive investments in natural capital (Fig. 5) show the interaction between adaptation and mitigation investments, which act here as substitutes. Better quantifying the costs and benefits of these adaptive investments would help constrain this effect. Important future steps involve developing a regional model to explore heterogeneity in the importance of natural capital for human welfare in different countries to explicitly model the distributional implications of ecological damages from climate change[46], analysing optimal climate policies under epistemic uncertainty using robust decision-making lenses and investigating the effects of including in this framework non-climate drivers of natural capital degradation.

Methods

We modified and extended the 2013R DICE model[25] using the Mimi Framework (https://www.mimiframework.org/), a Julia package for integrated assessment models[47,48]. We represented the use and non-use values of nature by untangling three different components of the utility function: 1) normal consumption goods, 2) ecosystem services (here defined as non-market goods heavily reliant on natural capital for production, such as recreation or cultural values) and 3) existence and bequest values. These goods are produced by different combinations of the three types of capital (manufactured, natural and human). Therefore, we modified the social welfare function in DICE to represent the components of social well-being and specified a function to represent the production function for each of these goods (Supplementary Table 6).

The social welfare function depends on two components. The first derivative is positive and the second derivative is negative with respect to both components (that is, it is increasing and quasi-concave in both components). The use value component ($c_t^{\sim}$) follows the structure proposed by Hoel and Sterner[16] and the work carried out by Drupp and Hänsel[18]. $c_t^{\sim}$ represents the level of current consumption per capita of a representative good at time t, and is composed of two imperfect substitutes: $c_t^{\sim} = \left[(1-s)c_t^{\theta} + se_t^{\theta}\right]^{1/\theta}$. The first element ($c$) is the consumption per capita of a comprehensive economic output and the second component (e) is the flow of a representative ecosystem service per capita, which captures the production of goods and services particularly reliant on natural systems (for example, recreation), except carbon sequestration, as DICE has a carbon cycle component that we leave unchanged because it is beyond the scope of this analysis. The parameter θ is the substitutability parameter and s represents the fraction of use values that we get from ecosystem services.

The non-use value component of the welfare function is simply represented by a flow of intangibles (i) that arise directly from natural capital (for example, existence value). Therefore, the overall representative flow of consumption (f) is derived from both use and non-use values that are imperfectly substitutable with each other, and follows a similar structure to above: $f_t = \left[c_t^{\sim\theta_2} + s_2 i_t^{\theta_2}\right]^{1/\theta_2}$, where θ_2 is the substitutability parameter between use and non-use values and s_2 is a scaling parameter that transforms the flow of intangibles into a utility value. Welfare (W) is given by $W = \sum_{t=2020}^{2300} e^{-\rho t} u(f_t)$, where ρ is the pure rate of time preference and, following the standard DICE model, the utility function ($u(f)$) incorporates a constant relative risk aversion (α) and is given by $u(f) = \frac{f^{1-\alpha}}{(1-\alpha)}$.

The three production functions that underlie each component of f use the Cobb–Douglas form (Supplementary Table 6). The production of market goods (Y) is given by $Y = aL^{\gamma_1}K^{\gamma_2}N^{\gamma_3}$. This modifies the standard DICE representation of production by separating natural capital (N) from manufactured capital (K) as an input to production[49]. The elasticity of production (γ_1) with respect to labour (L) was kept at 0.7, as in standard DICE, whereas γ_2 (the elasticity of production with respect to manufactured capital) was adjusted to account for the natural capital input and the elasticity of production with respect to natural capital (γ_3)[50]. This adjustment was calibrated using World Bank estimates of the global value of natural capital[28] and Organisation for Economic Cooperation and Development estimates of the role of natural capital in determining total factor productivity (a) once natural capital is taken into account[51] (Supplementary Information). This substantially expands previous efforts to include natural capital in DICE. For example, Hackett and Moxnes[29] included natural capital damages as a separate impact on economic output. However, they did not include natural capital as part of the model of economic production, which better reflects recent literature on comprehensive wealth accounting[28,51].

Similarly, ecosystem services arise from the interaction of population (parameterized by labour L), manufactured capital and natural capital[2,52]. However, to our knowledge, there are no studies that have estimated the parameters of a highly aggregate ecosystem services production function on a global scale. The results of a recent fine-scale global study by Chaplin-Kramer et al.[46] indicate that nature's contributions to people arise when ecosystem processes interact with population, and that manufactured capital does not play an important role. Therefore, given the limited evidence available to constrain the parameters of this production function, we assume that the ecosystem services production function is $E = aL^{\gamma_1}K^{\gamma_3}N^{\gamma_2}$, where the elasticities of production with respect to manufactured and natural capital have been exchanged, representing the greater reliance of use ecosystem services on natural capital (given that $\gamma_2 \gg \gamma_3$ in the preferred parameterization).

Finally, we modelled the production of non-use values (i) as a function of natural capital only. This captures primarily existence values (the value of knowing that species or certain ecosystems exist)[32] and was therefore modelled as being produced exclusively from natural capital, without capital or labour inputs. Specifically, we set $i = N^{\gamma_4}$, assuming the contributions of people and manufactured capital to be negligible and $\gamma_4 = 0.5$ to represent diminishing marginal benefits. As with the ecosystem service production function, there is little empirical evidence to support this parameterization, but sensitivity to this parameter is explored in the sensitivity analysis.

To represent climate damage to natural systems, we added a second damage function that allows warming from climate change to affect the stock of natural capital. The damage parameter α of this damage function, $N_{t+1} = \frac{N_t}{1+\alpha T^2}$, was calibrated to reflect the non-market damages of temperature (T) originally embedded in the DICE damage function. We followed the Drupp and Hänsel[18] calibration of the damage parameter by matching the damage level of the DICE 2013R model as given by Nordhaus and Sztorc[25], using the database of damage estimates collected by Howard and Sterner[53] to separate market and non-market damages as well as using the results of Hsiang et al.[54] to control for mortality (Supplementary Information).

It is important to note that in GreenDICE, the climate is damaging the natural capital stock, which potentially causes persistent losses in welfare. In contrast, other well-known models[16,18] introduced the climate impacts directly into the ecosystem services, causing mostly non-persistent impacts on the levels of consumption (Supplementary Information). Although the contemporaneous effects of higher temperatures were calibrated to match the DICE damage function (Supplementary Information), allowing these to accrue to natural capital rather than the level of output means that these damages persist in GreenDICE differently than in standard DICE. This means that the effects of total damages on any given temperature trajectory will be higher in GreenDICE.

The implementation of investments in natural capital as a third control variable for welfare-maximizing policy was carried out in two ways. First, in the Adaptive Investments specification we allow investments (I_t) to reduce the natural capital damages (D_{Nt}) by a fraction ad_t, following the standard DICE functional form $N_{t+1} = N_t - D_{Nt}(1 - \mathrm{ad}_t)$, producing a convex cost function (I_t) similar to the emissions abatement cost function in DICE: $I_t = Y_t \mathrm{ad}_t^w$. The parameter w was calibrated assuming that investing 2.1% of annual GWP in environmental protection would reduce 50% of climate damages and was varied in a sensitivity analysis (Supplementary Information and Extended Data Fig. 2). An alternative form of investment (Asset Investment) was introduced by allowing spending to directly increase the natural capital stock. The costs of these investments were based on the asset pricing literature[55], where the price of a unit of natural capital at time t ($p_{N,t}$), relative to the price of a unit of manufactured capital at time t is given by $p_{N,t} = \frac{\partial W_t/\partial N_t}{\partial W_t/\partial K_t}$. The model iteratively maximizes welfare by investing in natural capital based on this asset price until convergence of prices and investment is reached (see the Results and Discussion in the Supplementary Information).

It is important to note that GreenDICE is based on DICE-2013R, not the more recent DICE-2016R2, which includes new projections of population, economic growth and carbon intensity and begins in 2015 instead of 2010. These changes could change the specific numbers in the results, such as the projected emissions, which would start closer to 2020, but are very unlikely to alter any conclusions. This is particularly true because many of the updates to specific parameters in DICE-2016R2 have already been included in our sensitivity analysis, for example, the damage function parameter and the climate sensitivity.

Data availability

Results of the simulations are available at https://github.com/BerBastien/GreenDICE/tree/master/Results

Code availability

GreenDICE code is available at www.GitHub.com/BerBastien/GreenDICE

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References

1. Pascual, U. et al. Valuing nature's contributions to people: the IPBES approach. *Curr. Opin. Environ. Sustain.* **26**, 7–16 (2017).
2. De Groot, R. S., Alkemade, R., Braat, L., Hein, L. & Willemen, L. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecol. Complex.* **7**, 260–272 (2010).
3. Turner, R. K. et al. Valuing nature: lessons learned and future research directions. *Ecol. Econ.* **46**, 493–510 (2003).
4. Agarwala, M., Atkinson, G., Baldock, C. & Gardiner, B. Natural capital accounting and climate change. *Nat. Clim. Change* **4**, 520–522 (2014).
5. Jones-Walters, L. & Mulder, I. Valuing nature: the economics of biodiversity. *J. Nat. Conserv.* **17**, 245–247 (2009).
6. Gomes, V. H. F., Vieira, I. C. G., Salomão, R. P. & ter Steege, H. Amazonian tree species threatened by deforestation and climate change. *Nat. Clim. Change* **9**, 547–553 (2019).
7. Rogers, L. A. et al. Shifting habitats expose fishing communities to risk under climate change. *Nat. Clim. Change* **9**, 512–516 (2019).
8. Roberts, C. P., Allen, C. R., Angeler, D. G. & Twidwell, D. Shifting avian spatial regimes in a changing climate. *Nat. Clim. Change* **9**, 562–566 (2019).
9. Pecl, G. T. et al. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* **355**, eaai9214 (2017).
10. Settele, J. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds. Field, C. B. et al.) 271–360 (IPCC, Cambridge Univ. Press, 2015).
11. Warszawski, L. et al. A multi-model analysis of risk of ecosystem shifts under climate change. *Environ. Res. Lett.* **8**, 044018 (2013).
12. Parmesan, C. & Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**, 37–42 (2003).
13. *Global Assessment Report on Biodiversity and Ecosystem Services* (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019).
14. Millennium Ecosystem Assessment *Ecosystems and Human Well-being: Synthesis* (Island Press, 2005).
15. Drupp, M. A. Limits to substitution between ecosystem services and manufactured goods and implications for social discounting. *Environ. Resour. Econ.* **69**, 135–158 (2018).
16. Hoel, M. & Sterner, T. Discounting and relative prices. *Clim. Change* **84**, 265–280 (2007).
17. Sterner, T. & Persson, U. M. An even sterner review: introducing relative prices into the discounting debate. *Rev. Environ. Econ. Policy* **2**, 61–76 (2008).
18. Drupp, M. A. & Hänsel, M. C. Relative prices and climate policy: how the scarcity of non-market goods drives policy evaluation. *Am. Econ. J. Econ. Policy* https://www.aeaweb.org/articles?id=10.1257/pol.20180760 (2020).
19. Tol, R. S. The damage costs of climate change: a note on tangibles and intangibles, applied to DICE. *Energy Policy* **22**, 436–438 (1994).
20. Kopp, R. E., Golub, A., Keohane, N. O. & Onda, C. The influence of the specification of climate change damages on the social cost of carbon. *Economics-Kiel* **6**, 1–40 (2012).
21. Moore, F. C. & Diaz, D. B. Temperature impacts on economic growth warrant stringent mitigation policy. *Nat. Clim. Change* **5**, 127–131 (2015).
22. Tol, R. S. Estimates of the damage costs of climate change. Part 1: benchmark estimates. *Environ. Resour. Econ.* **21**, 47–73 (2002).
23. Diaz, D. & Moore, F. Quantifying the economic risks of climate change. *Nat. Clim. Change* **7**, 774–782 (2017).
24. Nordhaus, W. D. & Tobin, J. in *Economic Research: Retrospect and Prospect* Vol. 5 1–80 (NBER, 1972).
25. Nordhaus, W. & Sztorc, P. *DICE 2013R: Introduction and User's Manual* (retrieved November, 2019); https://go.nature.com/3kmwMc5
26. Barbier, E. B. The concept of natural capital. *Oxf. Rev. Econ. Policy* **35**, 14–36 (2019).
27. 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).
28. Lange, G.-M., Wodon, Q. & Carey, K. *The Changing Wealth of Nations 2018: Building a Sustainable Future* (The World Bank, 2018).
29. Hackett, S. B. & Moxnes, E. Natural capital in integrated assessment models of climate change. *Ecol. Econ.* **116**, 354–361 (2015).
30. Dietz, S. & Stern, N. Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. *Econ. J.* **125**, 574–620 (2015).
31. Glotter, M. J., Pierrehumbert, R. T., Elliott, J. W., Matteson, N. J. & Moyer, E. J. A simple carbon cycle representation for economic and policy analyses. *Clim. Change* **126**, 319–335 (2014).
32. Arrow, K. et al. Report of the NOAA panel on contingent valuation. *Fed. Regist.* **58**, 4601–4614 (1993).
33. Bateman, I. & Willis, K. (eds) *Valuing Environmental Preferences: Theory and Practice of the Contingent Valuation Method in the US, EU, and Developing Countries* (Oxford Univ. Press, 2001).
34. Champ, P. A., Boyle, K. J., Brown, T. C. & Peterson, L. G. (eds) *A Primer on Nonmarket Valuation* Vol. 3 (Springer, 2003).

35. *Technical Support Document: - Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866* (Interagency Working Group on Social Cost of Carbon, United States Government, 2010).
36. Beckage, B. et al. Linking models of human behaviour and climate alters projected climate change. *Nat. Clim. Change* **8**, 79–84 (2018).
37. Breiman, L. *Manual On Setting Up, Using, And Understanding Random Forests V3.1* https://www.stat.berkeley.edu/ breiman/Using_random_forests_V3.1.pdf (2002).
38. Lemoine, D. & Traeger, C. P. Economics of tipping the climate dominoes. *Nat. Clim. Change* **6**, 514–519 (2016).
39. Cai, Y. & Lontzek, T. S. The social cost of carbon with economic and climate risks. *J. Polit. Econ.* **127**, 2684–2734 (2019).
40. Traeger, C. P. A 4-stated DICE: quantitatively addressing uncertainty effects in climate change. *Environ. Resour. Econ.* **59**, 1–37 (2014).
41. Crost, B. & Traeger, C. Optimal climate policy: uncertainty versus Monte Carlo. *Econ. Lett.* **120**, 552–558 (2013).
42. Statistical Office of the European Union *Environmental Protection Expenditure Accounts: Handbook* (Eurostat, 2017).
43. Diaz, D. B. Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). *Clim. Change* **137**, 143–156 (2016).
44. De Bruin, K. C., Dellink, R. B. & Tol, R. S. AD-DICE: an implementation of adaptation in the DICE model. *Clim. Change* **95**, 63–81 (2009).
45. Urban, M. C. Accelerating extinction risk from climate change. *Science* **348**, 571–573 (2015).
46. Chaplin-Kramer et al. Global modeling of nature's contributions to people. *Science* **366**, 255–258 (2019).
47. Moore, F. C. et al. Mimi-PAGE, an open-source implementation of the PAGE09 integrated assessment model. *Sci. Data* **5**, 180187 (2018).
48. Anthoff, D., Plevin, R., Kingdon, C. & Rennels, L. *Mimi: An Integrated Assessment Modeling Framework* (2020); https://www.mimiframework.org/
49. Solow, R. M. Is the end of the world at hand? *Challenge* **16**, 39–50 (1973).
50. Stiglitz, J. E. in *Scarcity and Growth Reconsidered* (ed. Smith, V. K.) 36–66 (The Johns Hopkins Univ. Press, 1979).
51. Brandt, N., Schreyer, P. & Zipperer, V. Productivity measurement with natural capital. *Rev. Income Wealth* **63**, S7–S21 (2017).
52. Costanza et al. Changes in the global value of ecosystem services. *Glob. Environ. Change* **26**, 152–158 (2014).
53. 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).
54. Hsiang et al. Estimating economic damage from climate change in the United States. *Science* **356**, 1362–1369 (2017).
55. Yamaguchi, R. & Managi, S. Backward-and forward-looking shadow prices in inclusive wealth accounting: an example of renewable energy capital. *Ecol. Econ.* **156**, 337–349 (2019).

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Author contributions

B.A.B.-O. and F.C.M. conceived the study, analysed the results and prepared the manuscript. B.A.B.-O. coded the model and performed the simulations.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to B.A.B.-O.

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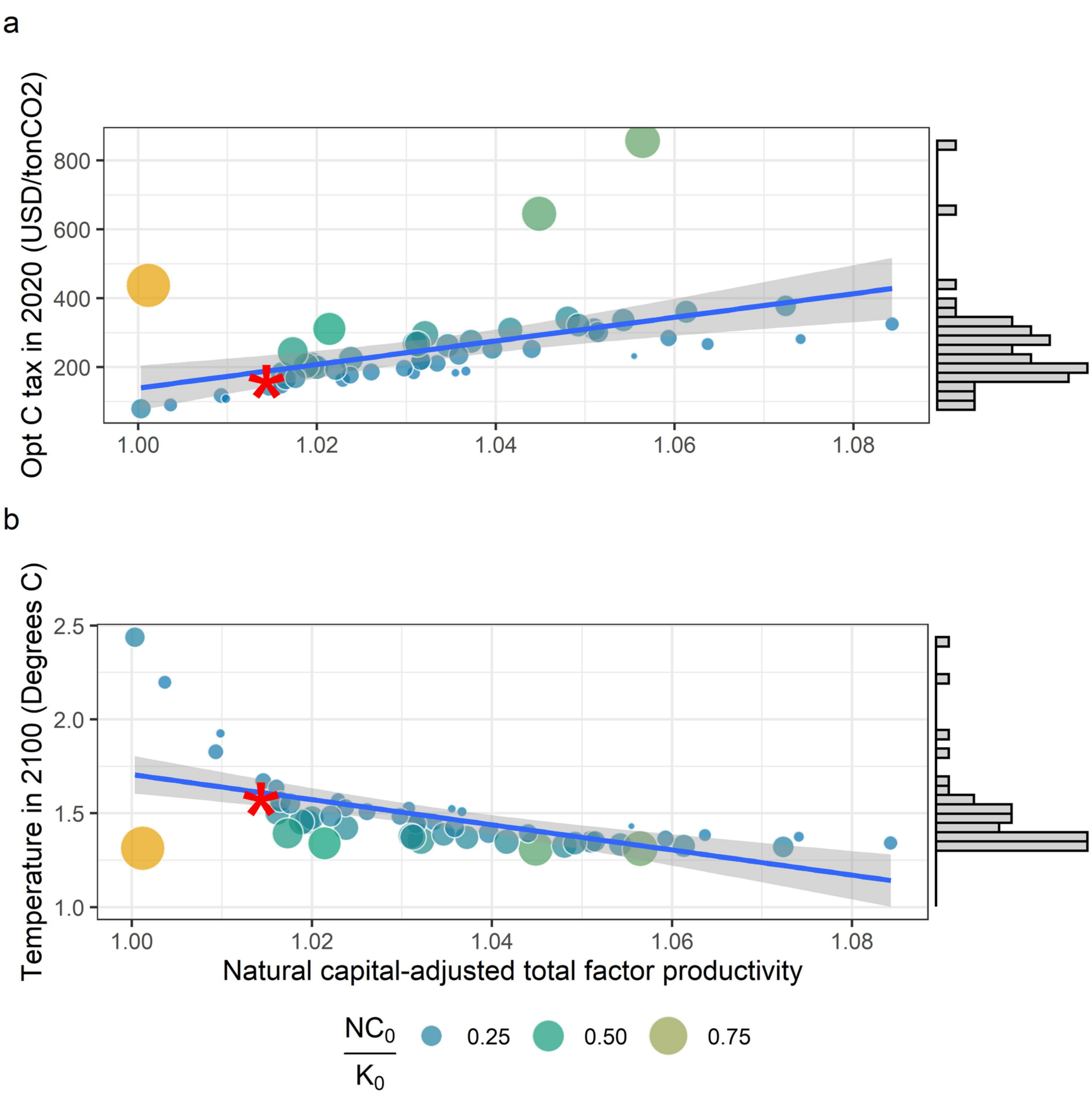
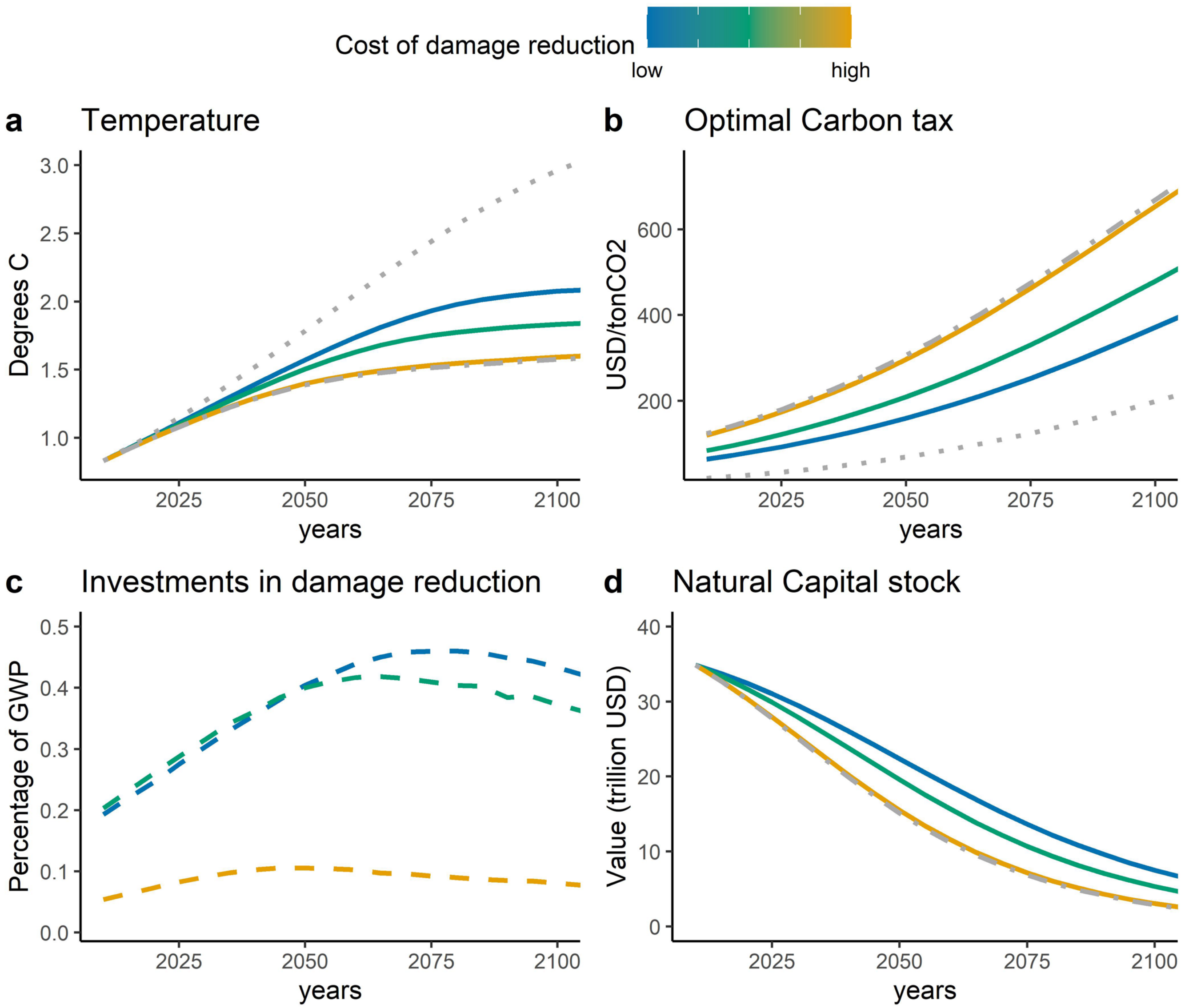
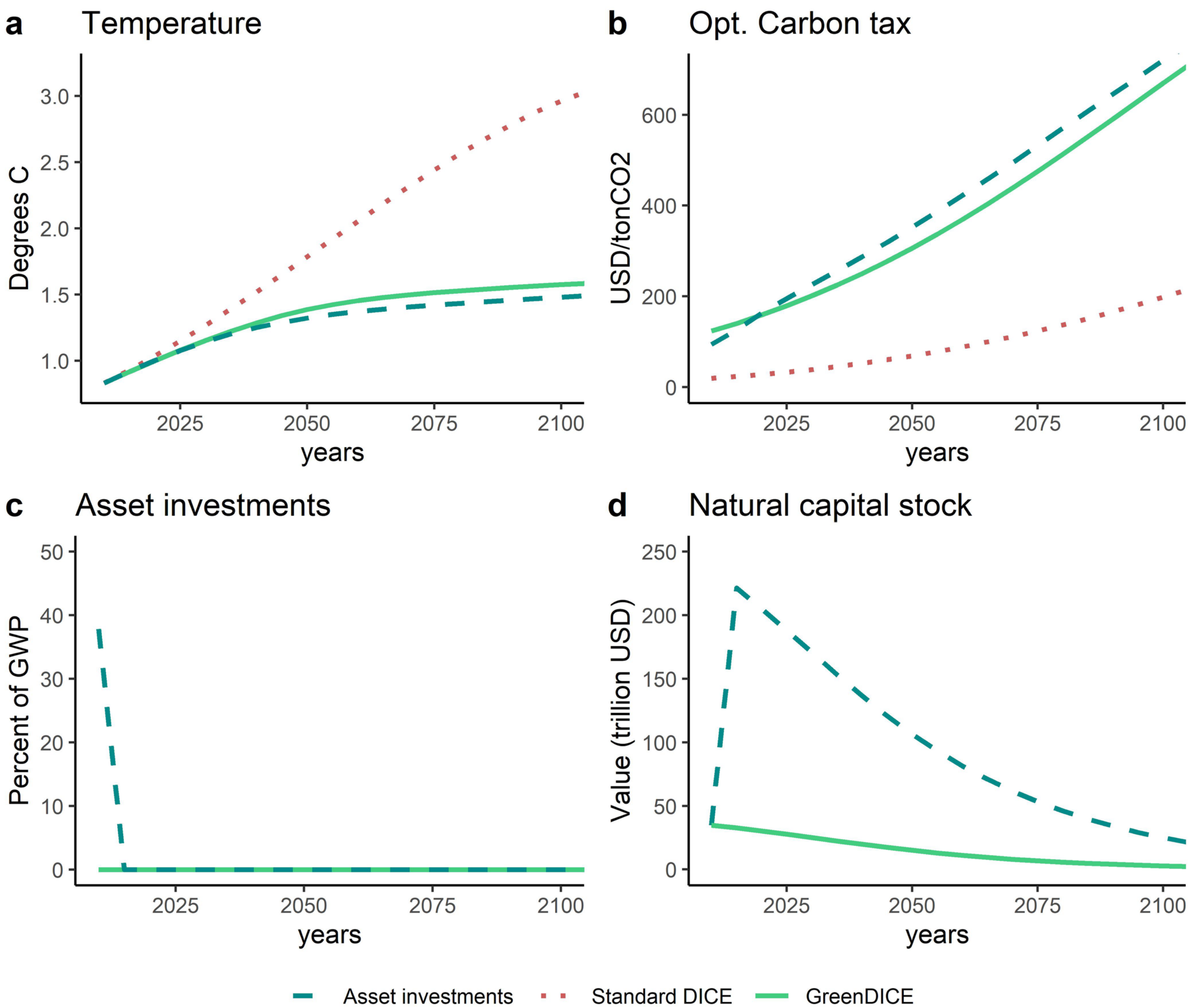


Extended Data Fig. 1 | Effects of different estimates of natural capital. Effects of different estimates of the natural capital-adjusted total factor productivity and natural capital current value relative to current manufactured capital. Red stars give values using the preferred parameter estimates. Size of circles represents the current global estimate of natural capital value with respect to manufactured capital.



Extended Data Fig. 2 | Three levels of adaptation costs. Key policy variables under welfare-maximizing conditions of three levels of adaptation costs. Dotted line is standard DICE, and dashed-dotted line is GreenDICE without investments.



Extended Data Fig. 3 | Investments on natural capital stock. Welfare-maximizing investments on natural capital stock.