Global warming, ecosystems and inequality

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Abstract

Global warming, biodiversity loss and inequalities are interconnected, yet rarely studied jointly. We investigate how damages to the environment change the social cost of inequalities, and how inequalities influence the social value of ecosystem services. We show that the answer depends on two parameters: inequality aversion, and substitutability between market goods and environmental goods. When both parameters are high, inequality increases the marginal value of the environment. This is not always the case when both parameters are low. We quantify this interaction by building a climate-economy model that includes ecosystem services and features both national and international inequalities. In our main calibration, the presence of national inequalities doubles the marginal social cost of damages to the environment. Overall, our findings show that inequalities and ecosystem services interact in large and non-obvious ways. Ignoring this interaction can lead to substantial errors in the evaluation of environmental and redistributive policies.

Keywords: Climate change, Ecosystem services, Inequality, Integrated assessment models.

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1 Introduction

Environmental crises affect people unequally. Developing countries have already suffered disproportionately from the impacts of global warming, and future damages will be concentrated on the poorest populations (IPCC 2023). Many of the world's poorest communities live in places where the highest damages to ecosystems are projected (IPBES 2019); while rural, low-income households are the ones who rely most on natural products for subsistence (Angelsen et al. 2014). Understanding the interactions between inequalities and the environment is crucial for policy design; neither can be understood without the other (Drupp et al. 2025).

In this paper, we answer the following question: Do climate damages to the environment increase the social cost of inequalities? Conversely, how do inequalities change the social cost of damages to the environment? We show that damages to the environment can either increase or decrease the social cost of inequalities, depending on two crucial parameters of the utility function. To quantify this effect, we build a climate-economy model with ecosystem services and national inequalities at the decile level. In our main calibration, within-country inequality doubles the social cost of damages to the environment. Results are highly sensitive to the model's parameters, in line with our theoretical predictions.

Our paper brings together three strands of the environmental economics literature: ecosystem valuation, climate change, and inequalities. Economists began valuing ecosystem services in the 1970s and 1980s, with the rise of cost-benefit analysis (Westman 1977; de Groot 1986; Hueting 1987). Valuation methods were refined in the 1990s (Daily 1997), and a first meta-analysis assessed the global value of nature's services (Costanza et al. 1997). The Millennium Ecosystem Assessment (UNEP 2003) and the Dasgupta review (2021) contributed to establishing ecosystem services as a central topic of environmental economics.

In parallel, the economics of climate change has mostly focused on how climate change impacts the production of market goods. This approach implicitly assumes that the impacts of climate change on welfare can be properly measured as changes in GDP. In the context of the debate on social discounting, Hoel and Sterner (2007), Sterner and Persson (2008), and Drupp (2018) argue that ecosystem services cannot be lumped together with standard consumption, because they are not fully substitutable with manufactured goods. As the economy grows, natural goods become relatively scarcer, and their marginal value increases. This concern has motivated recent efforts to distinguish between natural and manufactured goods in standard climate-economy models. Sterner and Persson (2008) and Drupp and Hänsel (2021) add a non-market environmental good to the Dynamic Integrated Climate-Economy model (DICE, Nordhaus 2007, 2018), and find large increases in the social cost of carbon. Bastien-Olvera and Moore

(2021) go further by also integrating natural capital in the production function, as well as non-use values of nature. Since they are all based on some version of DICE, none of these models feature economic inequalities. Bastien-Olvera et al. (2024) include ecosystem services in a country-level model that includes international inequalities (the RICE50+ model, from Gazzotti et al. 2021), but still lacks within-country inequalities.

Cost-benefit climate-economy models rarely have a fine representation of economic inequalities. The original Regional Integrated model of Climate and the Economy (RICE) developed by Nordhaus and Yang (1996) disaggregated the global DICE model into 10 regions. National inequalities were introduced by Dennig et al. (2015) with their Nested Inequalities Climate-Economy (NICE) model, which features 12 regions, each divided into 5 income quintiles. This model shows that within-region inequality has a large effect on the social cost of carbon. Further iterations on the NICE model increased its level of detail, with 176 countries and 10 deciles per country in the latest published version (Young-Brun et al. 2025).

Our contribution to this literature is twofold. The first one is a theoretical finding: with a standard social welfare function, damages to the environment can either increase or decrease the social cost of inequalities. Likewise, inequalities can either raise or lower the social cost of damages to the environment. The direction of the effect of environmental loss on the social cost of inequalities (and vice-versa) depends on two critical parameters of the social welfare function: inequality aversion and substitutability between manufactured and environmental goods. When both parameters are high, inequalities increase the marginal value of the environment, and environmental losses increase the marginal social cost of inequalities. When both are low, the opposite holds — except if both parameters are *very* low, in which case the sign of the effect depends on other model parameters and variables. This result contributes to understanding how standard social welfare functions behave in models with limited substitutability between market goods and ecosystem services.

Our second contribution is to quantify the effect of national inequalities on the social cost of damages to the environment. We introduce ecosystem services in the latest version of the NICE model (Young-Brun et al. 2025), updating the social welfare function to distinguish between manufactured goods and non-market environmental goods. The flow of ecosystem services decreases as global temperatures increase, following a damage function from Bastien-Olvera et al. (2024). We call this model GreenNICE. It is, to our knowledge, the first cost-benefit climate-economy model to integrate both ecosystem services and national inequalities. Our simulations show that the effect of national inequality on the social cost of environmental damages is highly sensitive to inequality aversion and substitutability. In our central calibration,

the presence of national inequality doubles the social cost of damages to the environment. If natural goods are less substitutable, the effect of national inequality becomes smaller in relative terms and is even reversed for low inequality aversion. Our main calibration is based on a narrow subset of ecosystem services. If we assume a 100-times-larger flow of ecosystem services, the social cost of damages to the environment grows by a factor of 7, and remains approximately twice as large with national inequalities than without.

Taken together, our results show that national inequalities and ecosystem services should be considered together in climate-economy models, as their interactions can change simulation results in significant and non-obvious ways.

In the next section, we explain why inequality can either increase *or* decrease the marginal value of nature. We then use simulations to quantify this effect for a range of parameterizations: section 3 explains how we integrate ecosystem services into the NICE model, and section 4 reports simulation results. We discuss the implications and limitations of these results in section 5. The final section concludes.

2 Theoretical analysis

Our theoretical finding is the following: within-country inequality can either increase *or* decrease the marginal value of ecosystem services, depending on inequality aversion and substitutability between consumption goods and the environment. We start by introducing our framework (2.1). Then, we state our result formally and explain the intuition behind it (2.2).

2.1 Framework

To study the interaction between within-country consumption inequalities and the environment, we combine these two variables in a two-good social welfare function. In this sub-section, we explain how we model inequality, what we mean by "the environment", and how these two components fit together in a social welfare function.

Inequality

We consider a set of m countries. The population L_i of each country $i \in \{1, \dots, m\}$ is divided into n consumption quantiles. Consumption $c_{i,j}$ of quantile j in country i can be defined as a function of the country's average consumption c_i, and some constant $\delta_{i,j}$:

$$c_{i,j} = c_i(1 + \delta_{i,j}\,\gamma).$$

Constant $\delta_{i,j} = (\hat{c}_{i,j} - c_i)/c_i$ is the relative difference between the observed consumption $\hat{c}_{i,j}$ of income group j and national average c_i. In this paper, we are interested in comparing situations with different levels of economic inequality. We introduce parameter $\gamma \in [0, 1]$ to arbitrarily vary the level of within-country inequality. When $\gamma = 0$, there is no national consumption inequality: the average consumption of an income group is the average consumption of its country. When $\gamma = 1$, national inequalities are fully implemented. This parameter is the same for all countries. Note that, by construction, parameter γ only changes the spread of the income distribution, without changing the mean. For any given country i, inequality coefficient γ is directly applied to the actual observed standard deviation of the country's income distribution, $\hat{\sigma}_i$:

$$\sigma_i = \gamma \cdot \hat{\sigma}_i.$$

See Appendix B for a formal derivation.

Non-market environmental goods

Nature contributes to human lives, producing "a flow of beneficial goods and services over time" (Barbier 2013). Natural capital is the stock of natural assets that produce a stream of benefits over time. These benefits are called environmental goods, ecosystem services, or nature's contribution to people.

In its first global assessment report, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services classifies nature's contributions to people (NCPs) in 18 categories (IPBES 2019, chapter 2.3). These 18 categories fall into three broad types: regulating, material, and non-material NCPs. Regulating contributions are natural processes that help maintain a high-quality environment, like pollination, water cycle regulation, or filtration of soil pollutants (NCPs 1 to 10 in the IPBES classification). Material NCPs are energy (NCP 11), food and feed (12), natural materials and direct use of organisms for company, transport and labor (13), and medicinal, biochemical and genetic resources (14). Non-material NCPs include inspiration and learning (15), physical and psychological experiences (16), and support to cultural identities (17). NCP 18 is the option value of the environment.

In the present paper, we focus on non-market NCPs: ecosystem services that do not enter the production of market goods. We define variable E as the annual per-capita flow of non-market environmental goods and services provided by a given natural capital stock N. We assume that ecosystem services that contribute to market outputs are already valued through consumption c. For example, E does not include fish from commercial fisheries, as they are a sold to consumers, but does include fishing for direct consumption or recreation. Restricting E to non-market

ecosystem services avoids double counting.

In the IPBES classification, our environment variable E corresponds to the non-market part of material and non-material NCPs (NCPs 11-17). Environment-regulating processes (NCPs 1 to 10) are only included to the extent that they directly contribute to human welfare. For example, we exclude pollination and dispersal of seeds (NCP 2) from E, as it only contributes indirectly to human welfare, through the production of other ecosystem services. We also exclude bequest value and the intrinsic values of nature (nature for its own sake).[1]

Countries have different initial endowments of natural capital, leading to different initial levels of E. Due to a lack of high-quality sub-national data on access to ecosystem services, we assume that environmental benefits are distributed equally across income groups.

Changes in E are only caused by climate damages. Global warming is currently the third largest direct driver of environmental loss, behind land- and sea-use change and direct exploitation of organisms (IPBES 2019, SPM, B1). However, the impact of global warming is accelerating, and might exceed that of land use by 2070 (Newbold 2018). In our model, we focus on climate damages, and abstract from environmental damages caused by other drivers. Including them would likely increase the marginal impact of environmental loss.

Social welfare function

Following Hoel and Sterner (2007), Sterner and Persson (2008), and Drupp and Hänsel (2021), we define utility as a function of consumption c and non-market environmental good E:

$$u : (c, E) \longmapsto \frac{\left[(1-\alpha)c^{\theta} + \alpha E^{\theta}\right]^{(1-\eta)/\theta}}{1-\eta}, \tag{1}$$

where $\alpha \in (0, 1)$ is the share of ecosystem services in the utility function, and $\theta \in (-\infty, 1] \setminus \{0\}$ is the degree of substitutability between consumption and non-market environmental goods.[2] Consumption and ecosystem services are perfect complements for $\theta \to -\infty$, and perfect substitutes for $\theta = 1$. Parameter η is a positive number different from one.[3]

There are two different ways of seeing parameter η. It can be interpreted as society's level of aversion to inequality. In that case, it is a normative parameter, that only makes sense at the social level. Alternatively, η can be understood at the individual level, as the inverse of the constant intertemporal elasticity, as the constant coefficient of relative risk aversion (CRRA),

[1] This departs from the GreenDICE model (Bastien-Olvera and Moore 2021), where the environment also has non-use value, like support to cultural identities and bequest value.

[2] The $\theta = 0$ case corresponds to a Cobb-Douglas function (Hoel and Sterner 2007): $u : (c, E) \mapsto \frac{[c^{1-\alpha}E^{\alpha}]^{1-\eta}}{1-\eta}$.

[3] The utility function can also be extended to the $\eta = 1$ case: $u : (c, E) \mapsto \ln[(1-\alpha)c^{\theta} + \alpha E^{\theta}]$.

or as the elasticity of marginal utility of consumption. In these interpretations, η also implies a form of inequality aversion, as a consequence of diminishing marginal utility. Because this paper focuses on inequalities, we will mainly refer to η as inequality aversion, without excluding other interpretations.

Social welfare is the sum of individual utilities. In each country i, social welfare can be written as a function of consumption and ecosystem services:

$$W = \sum_{i=1}^{m} L_i \cdot \frac{1}{n} \sum_{j=1}^{n} u\big(c_{i,j},\, E_i\big), \tag{2}$$

with L_i the country's population, and n the number of quantiles per country.

2.2 Interaction between inequality and ecosystem services

The extent to which inequalities interact with environmental loss is directly linked to the cross derivative of social welfare with respect to environment E and inequalities γ. This cross derivative indicates how the marginal effect of E on welfare changes when inequality increases by one unit. We let $\partial^2_{E,\gamma}W$ denote this cross derivative. If the cross derivative is positive, the marginal effect of E will increase when inequality increases by one unit. If, on the contrary, the cross derivative is negative, then within-country inequalities reduce the marginal value of the environment. In that case, a more equal country would suffer more from marginal damages to the environment than a more unequal country, all else equal.

Due to the symmetry of second derivatives ($\partial^2_{E,\gamma}W = \partial^2_{\gamma,E}W$), the sign of the cross derivative also tells us about the effect of the environment on the social value of reducing inequality. If $\partial^2_{E,\gamma}W$ is positive, the marginal welfare cost of inequality is higher when environmental quality is high. Countries with high environment E would benefit more from income redistribution than countries with low ecosystem services, all else equal. Conversely, if the cross derivative is negative, environmental loss increases the marginal welfare cost of inequality. In that case, damages to the environment would make income redistribution more valuable at the margin.

Cross derivative $\partial^2_{E,\gamma}W$ is also interesting because it is part of the answer to another question: in the presence of ecosystem services, what is the effect of inequalities on the social cost of carbon? The social cost of carbon (SCC) is the marginal social cost of greenhouse emissions. It is usually expressed in dollars per ton of CO_2 equivalent. Van der Ploeg et al. (2023) propose a straightforward analytical formula for the social cost of carbon. The present value of climate damages caused by marginal emissions in the present is a discounted sum of future marginal welfare cost, divided by some marginal utility of consumption, to ensure the result

is in a monetary unit (van der Ploeg et al. 2023, equation 11). Adapting this formula to our discrete-time, two-good setting, we define the social cost of carbon as:

$$\text{SCC} = \frac{1}{\partial_1 u(\overline{c_0}, \overline{E_0})} \sum_t \beta^t \sum_{i,j} \left[\partial_{c_{i,j,t}} W_t \cdot (-\partial_{e_0} c_{i,j,t}) + \partial_{E_{i,j,t}} W_t \cdot (-\partial_{e_0} E_{i,j,t}) \right]. \tag{3}$$

At time t, in income group j of country i, damages $(-\partial_{e_0} c_{i,j,t})$ are caused to consumption by additional marginal present emissions e_0. These damages are multiplied by the marginal social value of consumption, $\partial_{c_{i,j,t}} W_t$. The resulting product is the welfare cost of climate damages to consumption. Likewise, damages to the environment $(-\partial_{e_0} E_{i,j,t})$ are multiplied by marginal value $\partial_{E_{i,j,t}} W_t$ to obtain their welfare cost. Welfare costs of damages to consumption and to the environment are summed across all income groups and countries. The global welfare cost series is then aggregated across time, with utility discount factor $\beta = 1/(1+\rho)$ and rate of pure time preference ρ. Finally, the present welfare cost is converted to dollars by dividing it by marginal utility of consumption $\partial_1 u$, evaluated at average present consumption $\overline{c_0}$ and average present environment $\overline{E_0}$. This conversion factor does not vary with inequality coefficient γ. When calculated this way, the social cost of carbon is the present social value of climate damages, expressed in dollars, from the point of view of a theoretical person living in the present at the average level of consumption and environment.

In this paper, we are specifically interested in the environmental part of the social cost of carbon. We decompose the SCC as the sum of a consumption part and an environmental part:

$$\text{SCC} = \text{SCC}_c + \text{SCC}_E,$$

with

$$\text{SCC}_c = \frac{1}{\partial_1 u(\overline{c_0}, \overline{E_0})} \sum_t \beta^t \sum_{i,j} \partial_{c_{i,j,t}} W_t \cdot (-\partial_{e_0} c_{i,j,t})$$

and

$$\text{SCC}_E = \frac{1}{\partial_1 u(\overline{c_0}, \overline{E_0})} \sum_t \beta^t \sum_{i,j} \partial_{E_{i,j,t}} W_t \cdot (-\partial_{e_0} E_{i,j,t}).$$

The marginal effect of within-country inequality on the environmental component of the social cost of carbon is given by the derivative of SCC_E with respect to inequality coefficient γ:

$$\partial_\gamma \text{SCC}_E = \frac{1}{\partial_1 u(\overline{c_0}, \overline{E_0})} \sum_t \beta^t \sum_{i,j} \partial_\gamma \partial_{E_{i,j,t}} W_t \cdot (-\partial_{e_0} E_{i,j,t}).$$

The marginal utility of consumption, the discount factor, and the negative of the marginal

damage to the environment have positive values. Therefore, the sign of $\partial_\gamma \text{SCC}_E$ depends on the sign of the cross derivative of welfare with respect to γ and E. If the cross derivative is positive, then the environmental component of the social cost of carbon increases with within-country inequality. If the cross derivative is negative, then the SCC is lower when inequalities are high. If the cross derivative is sometimes positive and sometimes negative, then the effect of γ on SCC_E is indeterminate.

In Proposition 1, we show that with two income groups, the sign of cross derivative $\partial^2_{E,\gamma} W$ depends on inequality aversion η and substitutability θ. It is always positive when inequality aversion η is higher than complementarity $1-\theta$; always negative when η is between $-\theta$ and $1-\theta$; and indeterminate when $\theta < \eta$ (see Figure 1).

Proposition 1. *With two income groups, the sign of $\partial^2_{E,\gamma} W$ depends on parameters θ and η in the following way:*

1. *if $\eta > 1-\theta$, then $\partial^2_{E,\gamma} W > 0$,*
2. *if $-\theta < \eta < 1-\theta$, then $\partial^2_{E,\gamma} W < 0$,*
3. *if $\eta < -\theta$, then the sign of $\partial^2_{E,\gamma} W$ depends on α, on γ, on E and on average consumption, as well as on θ and η.*

Proof. See Appendix C. □

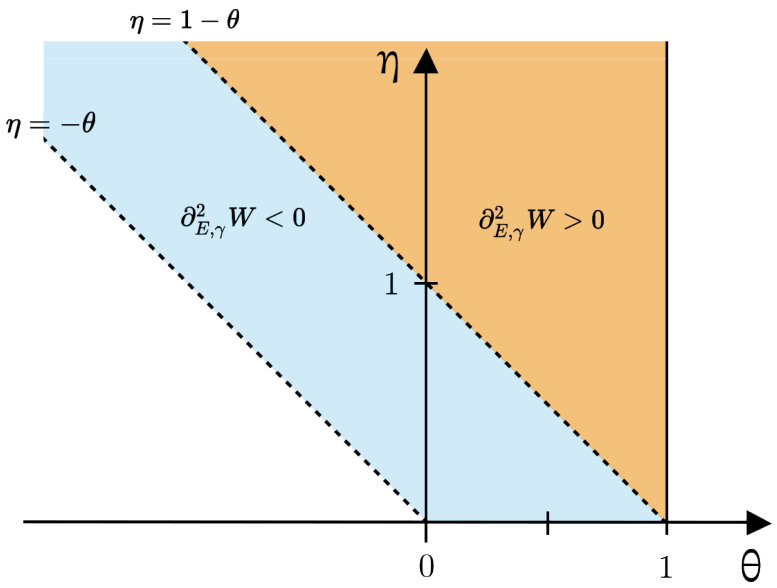


Figure 1: The sign of cross derivative $\partial^2_{E,\gamma} W$ depends on substitutability θ and inequality aversion η (Proposition 1).

Note: The plot shows how the cross derivative changes as a function of η and θ. The orange area indicates the region where the sign is positive. The light blue region indicates the values under which the cross derivative is negative. Within the white area, the sign of the cross derivative is indeterminate.

The division of the (θ, η) plane in three zones in Figure 1 is due to two competing effects. One effect comes from inequality aversion η, and the other from complementarity $1-\theta$. Inequality aversion η is the concavity of the utility function u. When utility is more concave, getting richer in one of the two goods makes the other less valuable at the margin. For instance, when there is more environment, market goods become less useful marginally, because many needs are already satisfied by nature. Likewise, being richer makes the wood of an additional tree less useful, because, for example, there might be substitutes for biofuels on the market. Notice that this is only true if ecosystem services and market goods are substitutable enough. When the two goods are highly complementary, an increase in one makes the other *more* valuable at the margin. With a more efficient stove, additional wood from the forest provides more energy. A more diverse fauna increases the willingness to pay for binoculars. So, the cross derivative of welfare with respect to the environment and *consumption* ($\partial_{E,c}W$) is positive when inequality aversion and substitutability are both high, and negative when they are both low.

As inequality γ increases, one group gets richer, while the other gets poorer. When inequality aversion η is higher than complementarity $1-\theta$, the consumption loss of the low-income group makes the environment more valuable at the margin. At the same time, the environment becomes less marginally useful to the high-income group, as it gets slightly richer — but the effect of the low-income group is stronger.

When inequality aversion η is *lower* than complementarity $1-\theta$, the consumption loss of the low-income group makes the environment *less* valuable at the margin. At the same time, the environment becomes *more* marginally useful to the high-income group. Here, the effect of the low-income group is not always stronger. The lower-income group still drives the result when $\eta > -\theta$ (blue area on the figure). When $\eta < -\theta$ (white area), which effect wins depends on the level of inequality, on the balance between c and E, and on the other parameters of the social welfare function.

In this section, we showed how the sign of the interaction effect between inequality and environmental loss depends on substitutability and inequality aversion. In the following section, we present the climate-economy model that we build to quantify this interaction effect.

3 Making NICE green

To quantify the interaction between inequalities and environmental loss, we develop a new climate-economy integrated assessment model (IAM). This model calculates the welfare impacts of global warming on both the economy and the environment, at a high level of resolution (income deciles within each country). We call this model GreenNICE. All code used for this

model is available on GitHub.[4]

IAMs are economic growth models designed to study the interaction between climate change and the economy, and assess the impact of different climate policies. In these models, economic output is a function of labor, capital, and total factor productivity. A fraction of this output is reinvested to increase capital, while the remainder is consumed. Social welfare is typically modeled by a an increasing and concave function of consumption. Economic activity leads to greenhouse gas emissions, increasing global temperature. Changes in temperature feed back into the model through a *damage function* that reduces output.

Our GreenNICE model is based on the latest calibration of the NICE model (Young-Brun et al. 2025). It uses country-level data to set the initial values for GDP, population, and consumption decile distribution. The damage function for country-level economic output is a quadratic function of local temperature anomalies. It is calibrated on estimates from Kalkuhl and Wenz (2020). The climate module of NICE is the FaIR model (Leach et al. 2021). We set the emission abatement rate such as to obtain a temperature trajectory that is compatible with the 2°C target of the Paris agreement. Temperature starts at +1.17°C in 2020, and stabilizes slightly below +2° at the end of the model horizon (see Figure A.1).

3.1 Ecosystem services

GreenNICE departs from NICE by introducing ecosystem services in the social welfare function (Equation 2). In our main calibration, we restrict environment E to non-market goods provided by forests. We calibrate this variable with data from the Changing Wealth Of Nations database (CWON World Bank 2024).

This database contains values for three kinds of forest services: recreation, non-wood forest products, and water services. Recreation is part of NCP 16 (physical and psychological experiences) in the IPBES classification. In the CWON report, "non-wood forest products" mostly include food and feed (NCP 12), but also some non-wood raw materials (NCP 13). "Water services" mostly correspond to water quality (NCP 7) and quantity, location, and timing (NCP 6).

The CWON database contains values for the *stock* N_i of natural capital in each country i. These values are obtained by aggregating a flow of forest ecosystem services over the next 100 years, with a 4% discount rate (World Bank 2024, chapter 7, p. 145, equation 6). To recover the yearly flow of forest ecosystem services, we apply the reverse formula:[5]

[4] https://github.com/rturquier/GreenNICE

[5] See Appendix F for a detailed derivation.

$$E_{i,t} = N_{i,t} \left(\frac{0.04}{1 - (1 + 0.04)^{-100}} \right). \tag{4}$$

Monetary units are converted to 2017 USD for consistency.

Some countries of our model are missing in the CWON database. For these countries, we set initial natural capital N to match the closest country with a similar forest cover in 2020, as reported by the World Bank. Island states with missing data are matched to other island states based on similarity in land area. We provide a detailed list of matched countries in Appendix D.

Figure 2 shows the initial flow $E_{i,2020}$ of ecosystem services for each country i, divided by population. Initial levels are relatively low for most countries. The highest baseline environment per capita (in USD per year) are New Zealand ($690.8), Australia ($604.27) and Bhutan ($545.07). Four small countries have zero initial environment (Kuwait, Macau, the Maldives, and Qatar). We exclude these four countries when calculating the social cost of carbon, because their marginal value of the environment ($\partial_E W$) is infinite. There is no clear correlation between the initial level of ecosystem services and the level of inequality in a country.[6]

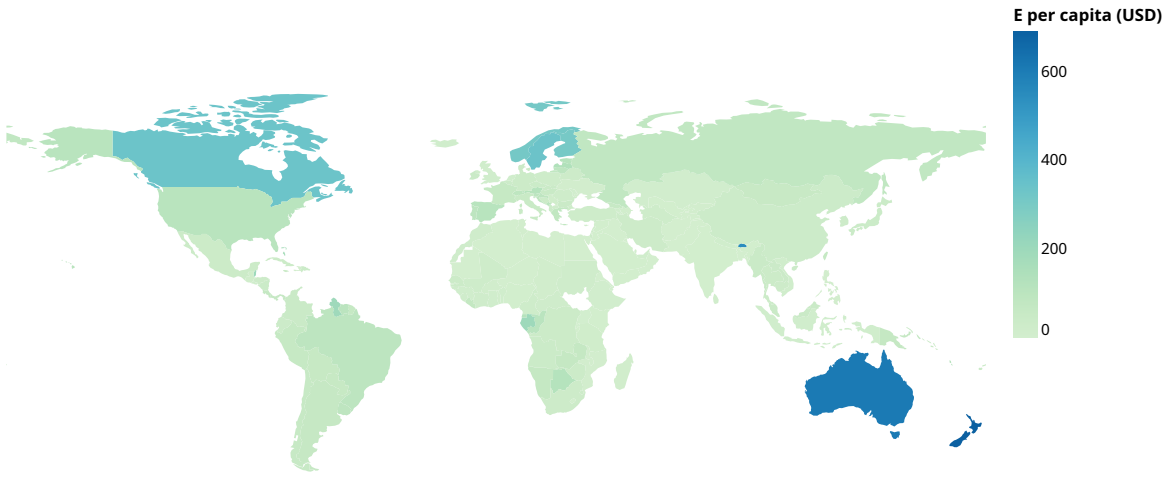


Figure 2: Flow of ecosystem services per capita in 2020 by country (USD)

Darker blue represents a higher initial flow of natural capital in dollars. The highest natural capital flow per capita is found in New Zealand.

We assume that everyone within country i benefits equally from the flow of ecosystem services ($E_{i,t}$). Consumption of the non-market environmental good does not exhaust the resource.

[6] See Figure A.2 for a plot of each country's Gini index against its initial value of E.

Natural capital stock $N_{i,t}$ only varies with temperature, according to the damage function introduced in the next subsection.

3.2 Environmental damage function

As global temperatures increase, vegetation shifts towards the poles (Bastien-Olvera et al. 2024). As biomes shift, the quantity of services they provide changes. We model this change with a linear damage function, following Bastien-Olvera et al. (2024). They calibrate the loss of non-market ecosystem services by retrieving climate-induced terrestrial vegetation coverage scenarios from three dynamic global vegetation models and by obtaining a damage coefficient for each country via linear regression. The damage function for the stock of the non-market environmental good in country i and year t is:

$$N_{i,t} = N_{i,2020}(1 + \xi_i \Delta T_t), \tag{5}$$

with ξ_i being the country-level damage parameter, and ΔT_t the change in temperature between 2020 and year t (Bastien-Olvera et al. 2024, equation 14). The initial natural capital stock $N_{i,2020}$ is expressed in 2017 USD. It is then converted back to a flow of services using Equation 4.

This damage function makes two simplifying assumptions: damages are a linear function of temperature anomalies, and natural capital is independent of the state of the environment in previous years. Bastien-Olvera et al. justify the choice of a linear rather than convex damage function by stating that it "avoids overly high damages estimated with a low level of confidence outside the observed range".

For countries without an initial damage coefficient, the parameter is assigned according to a hierarchical rule. Priority is given to existing assignments; if none are available, we use the coefficient from the geographically closest country; for the remaining island states, we assign the damage coefficient of the Dominican Republic. We show how we input these missing values in Appendix E.

Figure 3 shows the values of damage parameter ξ by country. While most countries have a negative coefficient (meaning positive damages), 40 countries are expected to gain natural capital with global warming. Countries that lose the highest proportion of their environment are Kuwait ($\xi = -0.22$), Egypt (-0.18), and Libya (-0.18). The countries with the largest positive coefficients are Yemen (0.19), Eritrea (0.13), and Oman (0.13).

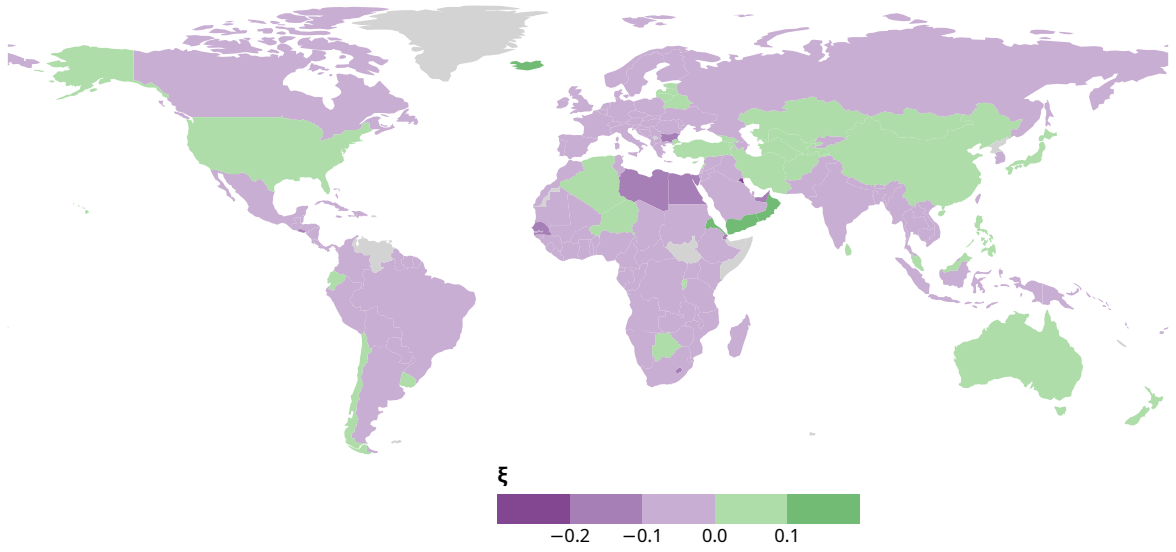


Figure 3: Spatial distribution of environmental damage coefficient ξ

Note: Purple represents a negative coefficient, resulting in natural capital loss due to climate change. Dark purple represents larger damage. The green color indicates a positive value of ξ. This implies an increment in natural capital. Darker green represents larger increments.

While this calibration might seem surprising at first, several factors can explain why forest services increase with global warming in some regions. Higher temperatures and precipitations at certain latitudes and altitudes can favor some species of trees. Higher concentrations of CO_2 in the atmosphere has a fertilization effect, increasing biomass production. However, the increased frequency and scale of wildfires might counterbalance these effects. Furthermore, ecosystem services do not only depend on forest cover or biomass. For example, medicinal, biochemical, and genetic resources (NCP 14, not included in CWON data) also depend on certain species not being extinct. Despite these limitations, this environmental damage function is the only one we could find that provides damage coefficients at the country level. It should be seen as an illustrative starting point, to be improved in further iterations of the model.

3.3 Inequality and social welfare function parameters

We keep the same consumption-share-by-decile projections as Young-Brun et al. (2025). Young-Brun et al. assume that income distribution follows a log-normal distribution, and estimate income shares until 2100 using Gini index projections from Rao et al. (2019). They then use a vectorial transformation (Pinkovskiy and Sala-i-Martin 2009) to derive consumption shares by country.[7] We also keep the default NICE value for the income elasticity of damages. This

[7]See Young-Brun et al. (2025, section 4.1) for a detailed explanation.

elasticity controls how climate damage to consumption is distributed across income groups. A value of 1 implies that damages are proportionally distributed, which results in a lower cost of carbon (Dennig et al. 2015). The default value for this parameter, 0.6, is based on empirical estimates from Gilli et al. (2024).

Parameters of the social welfare function do not have a single consensual value. We follow Drupp and Hänsel (2021) to set the default values of environmental weight α and substitutability parameter θ. Drupp and Hänsel find that, in the literature, values for α spans from 0.1 to 0.29. We set $\alpha = 0.1$, as a conservative assumption. Values reported for substitutability θ span from -0.43 to 0.9, with an average of 0.43 for all non-market environmental goods (Drupp and Hänsel 2021, table 2). We set $\theta = 0.43$ in our central calibration. We also present results with different values of θ, given that model outputs are highly sensitive to this parameter. Values for η are most frequently between 1 and 2, although values outside this interval are sometimes used or reported. We set $\eta = 1.5$, which corresponds to the default value in NICE (Dennig et al. 2015) and previous integrated assessment models (Anthoff and Emmerling 2019). This value is also the best guess of Groom and Maddison (2013) based on empirical estimates, and close to the average expert opinion among economists and philosophers (Nesje et al. 2023). We set the rate of pure time preference (ρ) to 0.1%, following the Stern report (2007).

4 Quantifying the effect of national inequality on the social cost of climate damages to the environment

We use numerical simulations to quantify the effect of national inequality on the social cost of climate damages to the environment. We define interaction effect I as the difference between SCC_E with current levels of within-country inequality ($\gamma = 1$) and SCC_E without national inequalities ($\gamma = 0$):

$$I = \text{SCC}_{E\,|\,\gamma=1} - \text{SCC}_{E\,|\,\gamma=0}\,. \tag{6}$$

Interaction effect I is the social cost of damages to the environment due to the presence of within-country inequalities. We also introduce a relative interaction effect, $I_{\%}$, which is the *share* of the social cost of damages to the environment that is due to the presence of within-country inequalities:

$$I_{\%} = \frac{\text{SCC}_{E\,|\,\gamma=1} - \text{SCC}_{E\,|\,\gamma=0}}{\left|\text{SCC}_{E\,|\,\gamma=1}\right|}. \tag{7}$$

For example, a relative interaction effect of $I_{\%} = 50\%$ means that half of SCC_E is due to national inequality. We use the absolute value of the SCC_E in the denominator to preserve the sign of interaction I. The interaction effect can be negative for some values of θ and η (see Proposition 1). It can also be negative for some countries, depending on the sign of their damage function parameter ξ (see Figure 3).

4.1 Simulation results under the main parameterization

For our first simulations, we assume standard levels of inequality aversion ($\eta = 1.5$) and substitutability ($\theta = 0.43$). Under these parameters, Proposition 1 implies that cross derivative $\partial^2_{E,\gamma} W$ is positive. Hence, an increase in inequality should raise the cost of marginal damages to the environment, and increase benefits for countries with a positive ξ. Figure 4 shows how the social cost of carbon changes when within-country inequality increases. In our simulations, the social cost of carbon is the present value of climate damages due to an additional ton of CO_2 emitted in 2025, expressed in 2017 dollars. The SCC is decomposed in damages to consumption (SCC_c) and damages to the environment (SCC_E).

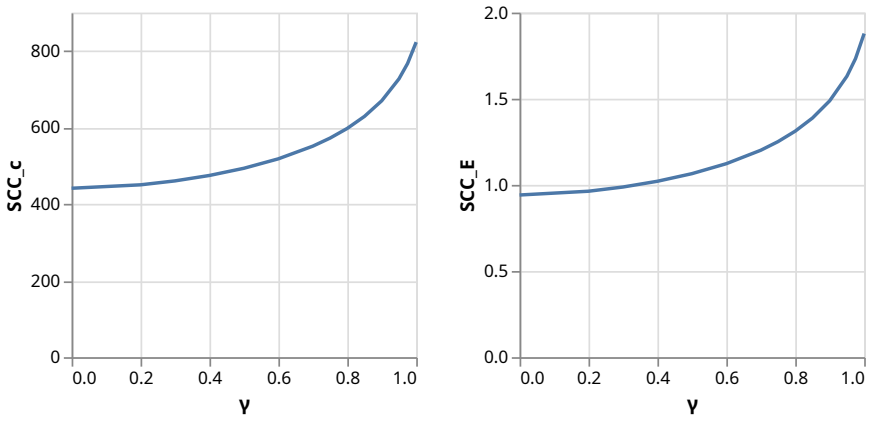


Figure 4: Social cost of carbon as a function of within-country inequality

Note: The left panel shows the social cost of damages to consumption caused by an additional ton of CO_2, in 2017 USD. The right panel shows the cost of damages to the environment. When $\gamma = 0$, there is no within-country inequality. When $\gamma = 1$, inequalities are fully implemented, based on the NICE2020 model.

With full national inequality, the total social cost of carbon is 824\$/tCO_2. This result is comparable to Anthoff and Emmerling (2019), who found a social cost of carbon of \$765.4 in the RICE model after accounting for intra-regional inequality. As predicted, SCC_E is an increasing function of γ. Damages to the environment amount to 0.94\$/tCO_2 when $\gamma = 0$. The presence of national inequality exactly doubles this cost to \$1.88 ($I = 0.94$\$). In other words, half of SCC_E is due to national inequality. Overall, under this calibration, damages to the environment represent a modest share of the total social of carbon, but double in the

presence of national inequality.

We show a decomposition of I and $I_{\%}$ by country in Figure 5 and Figure 6. Absolute interaction effect I ranges from \$0.36 to $-$\$0.03. The maximum cost increase is borne by India, followed by South Africa (\$0.12) and Zambia (\$0.08). The highest benefit augmentations are in Yemen, China ($I = -$\$0.02), and the USA ($I = -$\$0.02).

Relative interaction effect $I_{\%}$ is highest in South Africa (77.34%), Namibia (74.36%), and the Dominican Republic (68.24%). The countries whose benefits increase most (negative SCC_E) in relative terms are: Botswana ($I_{\%} = -74.27\%$), Rwanda ($I_{\%} = -58.48\%$), and Belarus ($I_{\%} = -57.03\%$).

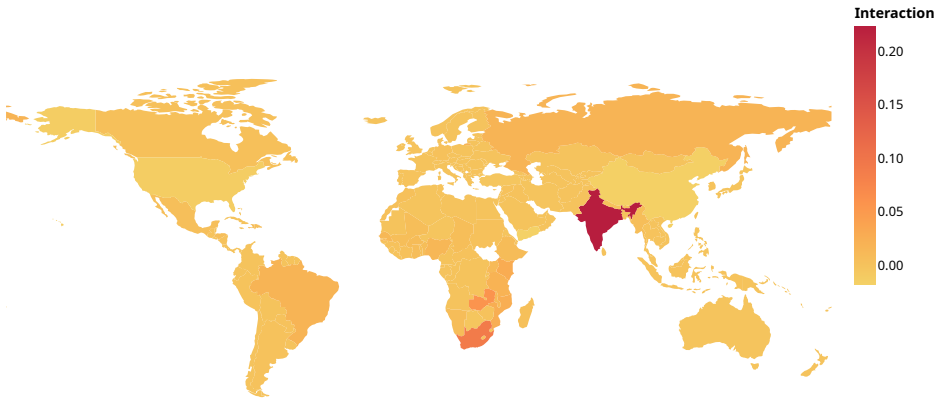


Figure 5: Absolute interaction effect I by country

Note: Dark red represents higher interaction effect measured in USD per ton of CO_2 equivalent. Yellow represents welfare gains from the interaction effect. This is the case when E increases with climate change.

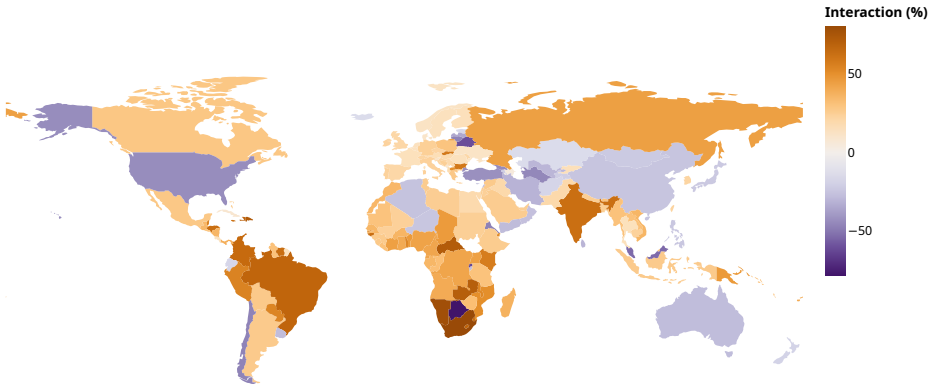


Figure 6: Relative interaction effect $I_{\%}$ by country

Note: Darker orange represents a larger share of the interaction effect with respect to total environmental damages. Darker purple represents the highest negative value, representing the share of the interaction effect with respect to welfare gains from the environment.

A negative I and $I_{\%}$ indicate that national inequalities reduce the social cost of damages to the environment. Here, countries with a negative interaction effect are all countries that have a positive ξ (compare with Figure 3). With $\eta = 1.5$ and $\theta = 0.43$, national inequalities increase the marginal value of the environment. Hence, when inequality increases, countries that were suffering environmental damages face higher costs, while countries that benefited from warming increase their benefits. Despite cross-country heterogeneity, damages exceed benefits at the global scale. So, the global interaction effect is positive: within-country inequality increases the social cost of damages to the environment. That is not always the case, as the next subsection shows.

4.2 Effect of inequality aversion and complementarity

We have shown in section 2 that the effect of inequality on the marginal value of the environment can be positive or negative, depending on the combination of η and θ. The simulations of the previous subsection are based on $\eta = 1.5$ and $\theta = 0.43$. In the literature, inequality aversion η is commonly set between 1 and 2. Drupp and Hänsel (2021) find that empirical estimates of substitutability θ between manufactured and environmental goods range from -0.42 to 0.9. Figure 7 shows SCC_E as a function of γ (as in Figure 4, right panel) for values of η ranging from 1 to 2 (rows) and for θ between -0.42 and 0.9 (columns).

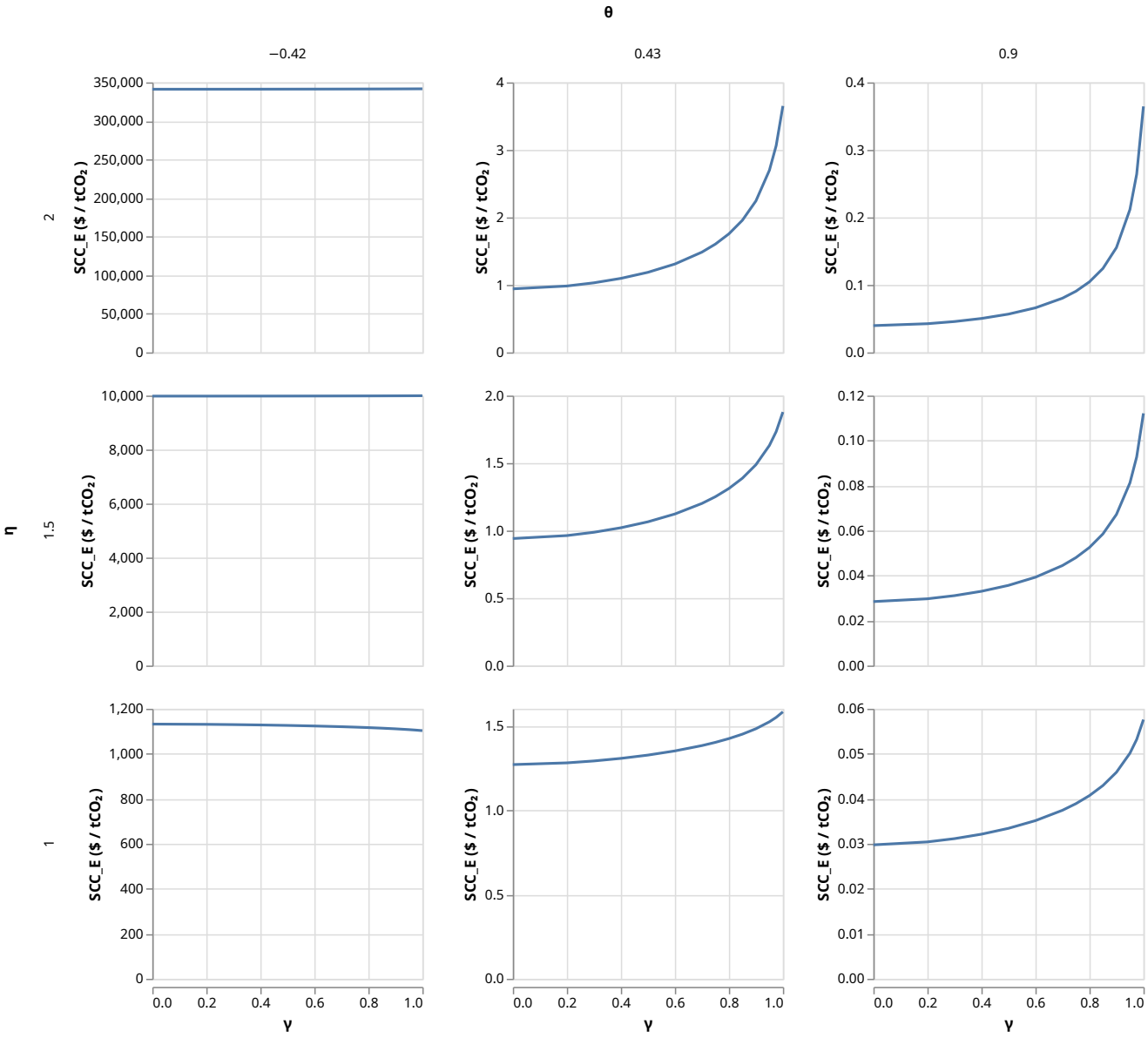


Figure 7: Evolution of SCC_E with respect to national inequality γ, for different values of substitutability θ and inequality aversion η

Note: Columns represent increasing levels of substitutability θ. Rows show SCC_E under different levels of inequality aversion η. The central panel shows the main calibration.

A first striking result is that the environmental part of the social cost of carbon increases steeply when substitutability is low, especially when η is high. In the low substitutability case ($\theta = -0.42$), the SCC_E rises from $\$1,100$ per ton of CO_2 to nearly $\$350,000$ per ton as inequality aversion η increases. On the other hand, under higher substitutability ($\theta = 0.9$), the social cost of damages to the environment amounts to only a few cents per ton, regardless of the degree of inequality aversion. This very high sensitivity to substitutability θ can partly be explained by the fact that the World Bank's valuation of ecosystem services is small relative to GDP. When environmental goods are rare but highly substitutable, damages are limited, as

lost ecosystem services can be easily replaced by human-made alternatives. By contrast, when environmental goods are difficult to replace, even a small loss of ecosystem services translates into large welfare losses.

A second noteworthy observation is that the relative effect of inequalities on SCC_E is also highly sensitive to θ. While national inequality doubles the social cost of environmental damages in the central scenario, it has little to no effect at lower substitutability levels. On the contrary, when $\theta = 0.9$, SCC_E is up to 9 times higher when $\gamma = 1$ than when $\gamma = 0$. The share of consumption damages in the total social cost of carbon also varies considerably with substitutability (a similar plot for SCC_c is provided as a supplementary figure for comparison — see Figure A.3).

A third visible result on Figure 7 is that national inequality can reduce the social cost of damages to the environment, as predicted by Proposition 1. The bottom-left panel shows a slight decrease of SCC_E as γ goes from 0 to 1. In this case, η and θ are such that $\eta \in (-\theta, 1-\theta)$. Therefore, inequality increases the marginal value of the environment. In all other panels, the interaction effect is positive (though it is close to zero for some).

Overall, inequality aversion η and substitutability θ are a critical pair of parameters. They drastically change the social cost of damages to the environment, both in absolute and relative terms. In one of the considered pairs of η and θ, the effect of national inequality is even reversed.

4.3 Sensitivity to the level of environment

The CWON data we use in our main simulation scenario only includes non-wood products, water services, and recreation services provided by forests: a fraction of the ecosystem services that should ideally be included. Some wood products are used as biofuel (NCP 11 in the IPBES classification) or construction (NCP 13), and fall in the scope of non-market ecosystem services. Medicinal, biochemical and genetic resources (NCP 14) provided by forests are also absent from this data. Moreover, other biomes also provide non-market ecosystem services. By focusing on forests, we only account for a small share of nature's contribution to people.

The CWON database values the global flow of non-market forest services at 256 billion USD per year. In comparison, Costanza et al. (2014) estimate that the value of all ecosystem services is about 147,500 billion USD per year — 577 times higher than in the World Bank report. Costanza et al. include all terrestrial and marine ecosystems, and most NCPs of the IPBES classification. They also include some market goods provided by ecosystems.[8] If restricted

[8]While the authors note that a certain share of their estimates comes from goods that are traded on markets, they argue that "much of it is not captured in GDP because it is embedded in services that are not marketed or not fully captured in marketed products and services". They do not precisely report the share of market versus

to water, food, and recreation services provided by forests, to approximate the scope of the CWON data, the Costanza et al. estimate is 6,900 billion USD per year. This number is still 27 times higher than the estimate of the World Bank.

As a sensitivity exercise, and using Costanza et al. (2014) as an upper-bound benchmark, we multiply the baseline level of ecosystem services E by factors ranging from 1 to 577 (Figure 8). Inequality aversion and substitutability are set to their central values ($\eta = 1.5$ and $\theta = 0.43$).

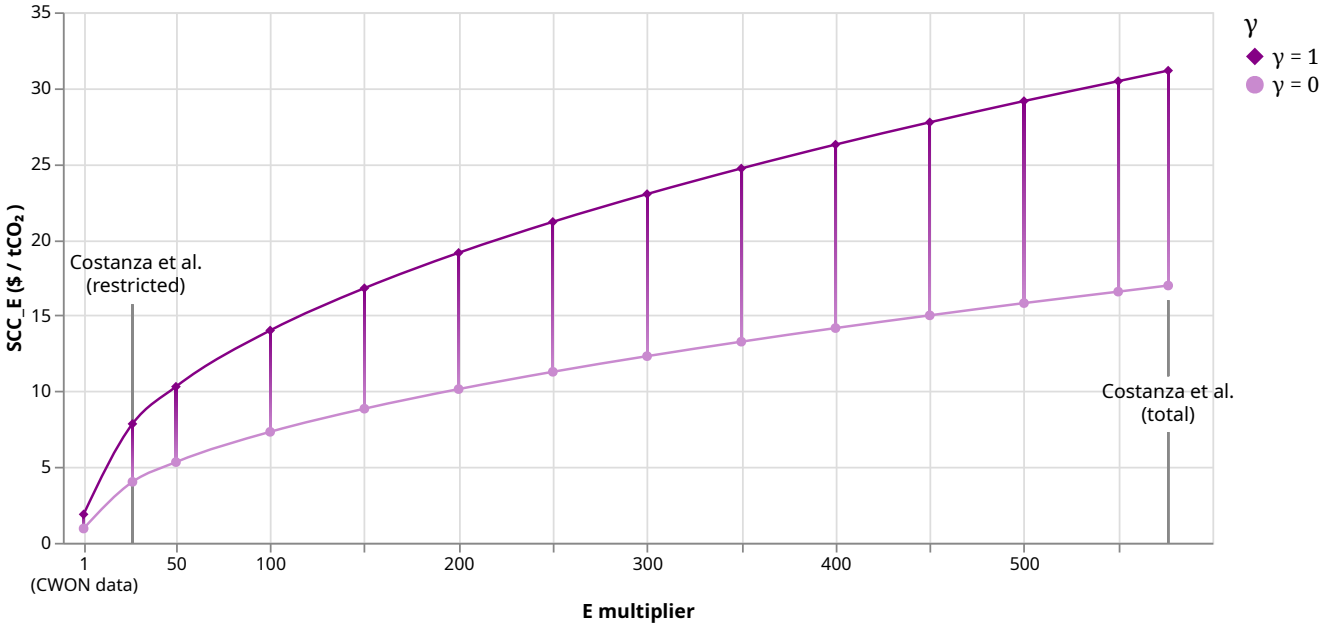


Figure 8: Sensitivity of SCC_E to baseline environment E

Note: This figure shows the evolution of SCC_E as the initial global flow of ecosystem services is multiplied by up to 577, in the presence ($\gamma = 1$) or absence ($\gamma = 0$) of national inequalities. An *E multiplier* of 1 corresponds to the baseline CWON data. Multiplying E by 27 brings it to the estimate of Costanza et al. (2014) restricted to recreation, food and water services provided by forests. The maximal factor of 577 matches the estimate of Costanza et al. for all services of all ecosystems. Interaction effect I is represented by the vertical lines between the two curves.

There are two opposing effects at play here. On the one hand, ecosystem services have diminishing marginal utility. On the other, more environment also means more environment to lose. As E increases, damages to E increase proportionally, but their social cost increases less than proportionally, because of diminishing marginal utility. The result is the concave increasing function shown on Figure 8.

When the level of environment is multiplied by 577 compared to the baseline scenario, SCC_E grows from \$1.88 to \$31.15 per ton (with national inequalities). In all considered calibrations of E, the presence of national inequalities approximately doubles the social cost of damages to the environment. In the baseline scenario, SCC_E is 2 times higher when $\gamma = 1$ (\$1.88) than

non-market ecosystem services.

when $\gamma = 0$ ($0.94). With values of E matching Costanza et al.'s total estimate, SCC_E is 1.73 times higher when $\gamma = 1$ ($31.15) than when $\gamma = 0$ ($16.97). In other words, the absolute interaction effect I goes from $0.94 to $14.18, while the relative interaction slightly declines from 50% to 45.5% (see Figure A.4 for a plot of $I_{\%}$).

Our main calibration only includes a fraction of ecosystem services. However, the relative effect of inequalities on SCC_E stays quite consistent, only declining slightly for much higher values of E. We can say more confidently that, for $\eta = 1.5$ and $\theta = 0.43$, the presence of national inequalities approximately doubles the social cost of damages to the environment.

5 Discussion

Because of different model specifications, SCC comparisons with previous work are difficult. Wingenroth et al. (2024) estimate that accounting for biodiversity loss implies an 8-dollar increase of the social cost of carbon. They reach this result by calculating the willingness to pay to prevent species loss and using these values as inputs to the GIVE model. This figure is higher than the social cost of damages to the environment in our central calibration (1.88 $/tCO$_2$), but our model would reach the same estimate by using a slightly lower substitutability.

Drupp and Hänsel (2021) calibrate the single-region DICE2016-R2 model (Nordhaus 2018) to account for non-market environmental damages. They find that the environment becomes more valuable as it becomes relatively scarce compared to manufactured goods. This relative price effect results in a 50% higher SCC, with a relatively low substitutability ($\theta = -0.11$). We have not run our model with this specific value of θ, which make a direct comparison difficult. In our model, with inequality aversion set to $\eta = 1.5$, SCC_c remains between $400 and $1,000 when θ goes from 0.43 to -0.42. For the same values of θ, SCC_E goes from $1.88 to $10,000 per ton of CO_2. It seems likely that there exists a θ between -0.42 and 0.43 such that SCC_E is equal to 50% of SCC_c.

In the GreenRICE model of Bastien-Olvera et al. (2024), natural capital provides utility to agents directly, while also entering the production function. Based on this specification, they estimate that environmental losses account for approximately 10% of total climate impacts in a +3.8°C scenario. With our more optimistic temperature trajectory (Figure A.1), our findings are lower under our central calibration, but are in the same ballpark for some specifications.

Overall, previous estimates of the environmental component of the SCC vary greatly. Under alternative sets of parameters, our model can reproduce a wide range of estimates. A more precise comparison exercise would be needed to investigate differences between models.

Our findings have several limitations that should be kept in mind when interpreting them. First, there is evidence that consumption inequality might be higher than in our calibration. The projections our model is based on assume that income distribution follows a log-normal distribution across deciles.[9] However, Narayan et al. (2023) show that, under a non-parametric distribution assumption, levels of inequality across different emissions scenarios are consistently higher. Using their projections would yield a higher interaction effect between inequality and ecosystem services.

Furthermore, our model simplifies how people benefit from natural capital. Our main calibration only considers benefits provided by forests, and assumes they are evenly distributed across income groups. Future work can make our central calibration more accurate by considering additional non-market goods supplied by other forms of natural capital, such as oceans (blue natural capital).[10] Relaxing the assumption of evenly distributed non-market goods would better reflect the physical and economic constraints that low-income groups face when accessing nature's contributions to people (Mirzabaev and Wuepper 2023). This would likely lead to a larger nature-inequality interaction effect.

Another limitation of our study is that we do not include nature as an input of the production function. The GreenDICE (Bastien-Olvera and Moore 2021) and GreenRICE (Bastien-Olvera et al. 2024) models incorporate this feature, as recommended by the Dasgupta review (2021). The inclusion of E in the production function would better represent the effects of ecosystem services loss on productivity. This would open a new channel through which climate change can affect human welfare, ultimately accentuating the interaction between natural capital and inequality. We decided to exclude this feature to keep the model tractable and focused on the social welfare function channel.

Finally, it is important to note that this paper focuses on climate-driven natural capital loss. Several other dynamics can alter natural capital over time. Land-use change can decrease forest cover, substituting it for agricultural or urban land uses (Johnson et al. 2021). Afforestation policies can increase the area covered by forests (Mirzabaev and Wuepper 2023) and other forms of natural capital. At the same time, sustainable management practices can make ecosystems more resilient to climate change (Cantarello et al. 2024). While relevant, these dynamics are beyond the scope of this paper.

[9] See subsection 3.3 for a brief explanation

[10] For instance, Bastien-Olvera et al. (2026) recently calculated the *blue* social cost of carbon, by assessing the cost of climate damages to certain coastal ecosystem services

6 Conclusion

In this paper, we study the interaction between inequality and natural capital loss. We use a constant elasticity of substitution utility function to account for the fact that individuals also directly derive utility from non-market environmental goods, which are not fully substitutable with market goods.

Our analytical result shows that environmental loss can either increase or attenuate the negative impact of inequality on welfare, depending on the relationship between inequality aversion and complementarity between market and non-market goods. When inequality aversion is greater than complementarity, a loss of income or nature makes the other asset more valuable at the margin. In that case, inequality increases the marginal cost of damages to the environment. Likewise, environmental loss increases the social cost of inequalities. This effect is reversed when complementarity is stronger than inequality aversion. In that case, higher inequality implies a lower marginal value of nature (except for extreme complementarity or very low inequality aversion, where the direction of the effect depends on other variables of the model).

We develop GreenNICE, the first cost-benefit integrated assessment model to integrate ecosystem services and within-country inequality in a single framework. In a +2°C scenario, the presence of national inequality accounts for 50% of the social cost of damages to the environment. Our results are very sensitive to inequality aversion and substitutability between manufactured and non-market environmental goods. In our central calibration, the interaction effect is \$0.94 per additional ton of CO_2. This result ranges from \$0.06 to roughly \$350,000 depending on the inequality aversion and substitutability parameters. A sensitivity exercise shows that the interaction effect increases to \$14.18 when the initial flow of non-market environmental goods is scaled up to match more comprehensive estimates in the literature. Altogether, our results show that the interaction effect between inequality and the environment can have very different magnitudes, and even change direction, depending on two critical parameters.

To the best of our knowledge, this is the first paper to examine the interaction between inequality and natural capital loss on welfare in an integrated climate-economy model. Our results offer an analytical and numerical framework to study this interaction. Our numerical results show that under most reasonable parameterizations, preserving ecosystems limits the social cost of inequality. Likewise, reducing inequality within countries can mitigate the welfare costs of climate-driven environmental loss. The high sensitivity to model parameters is an argument in favor of stronger environmental protection and income redistribution policies, as we still don't fully understand the total welfare impacts of climate change.

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A Supplementary figures

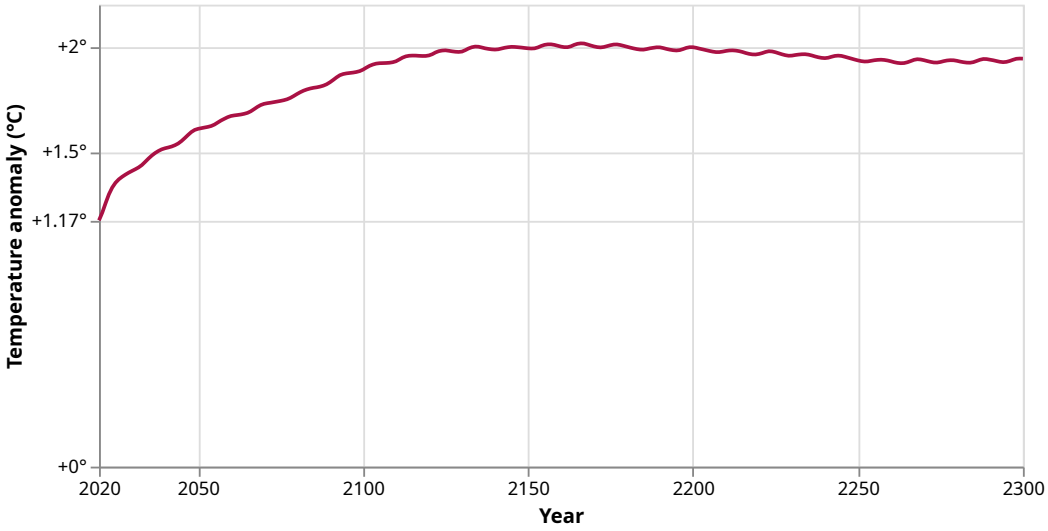


Figure A.1: Default temperature trajectory

Note: temperature anomaly is expressed relative to pre-industrial times. The exogenous abatement rate is set such that temperature stabilizes below the 2°C target of the Paris agreement in the long run. There is a slight overshoot in the middle of the twenty-second century. The subsequent cooling is caused by some of the greenhouse gases dissipating from the atmosphere.

Back to section 3.

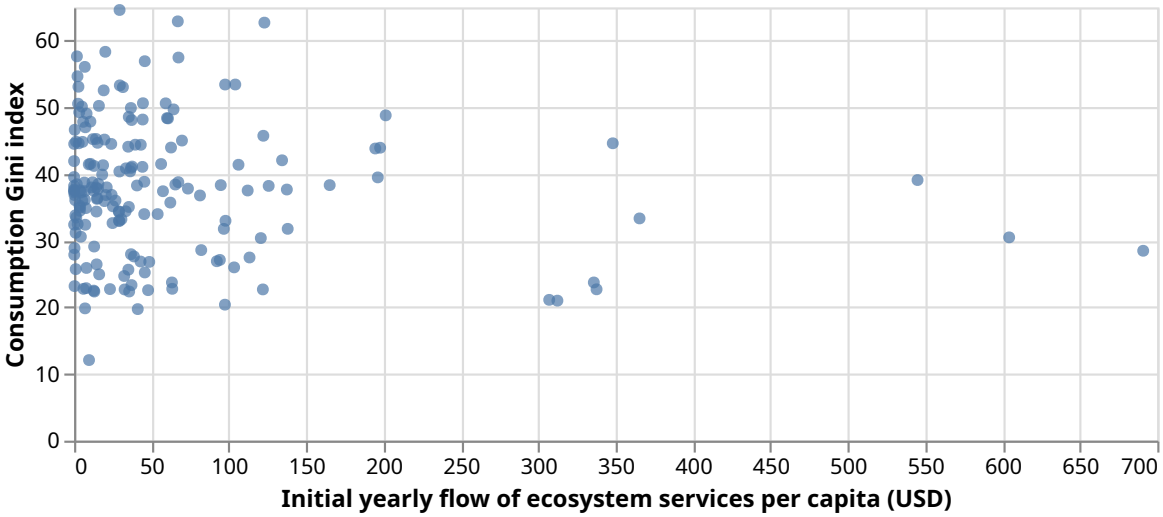


Figure A.2: Consumption gini index vs value of ecosystem services per capita in 2020

Note: Each dot represents a country. A larger Gini index indicates higher inequality. The countries with higher consumption Gini (higher consumption inequality) are South Africa, Namibia, and Botswana. The countries with the lowest consumption Gini index are Azerbaijan, Denmark, and Ukraine.
Finding the lowest consumption inequality in Azerbaijan is unexpected. Ersado (2006) argues that this figure is due to how data are collected in the country, pointing out that inequality should be higher. We keep this country in our sample to be consistent with previous research and because it is an observation that does not bias our aggregate results.

Back to subsection 3.1.

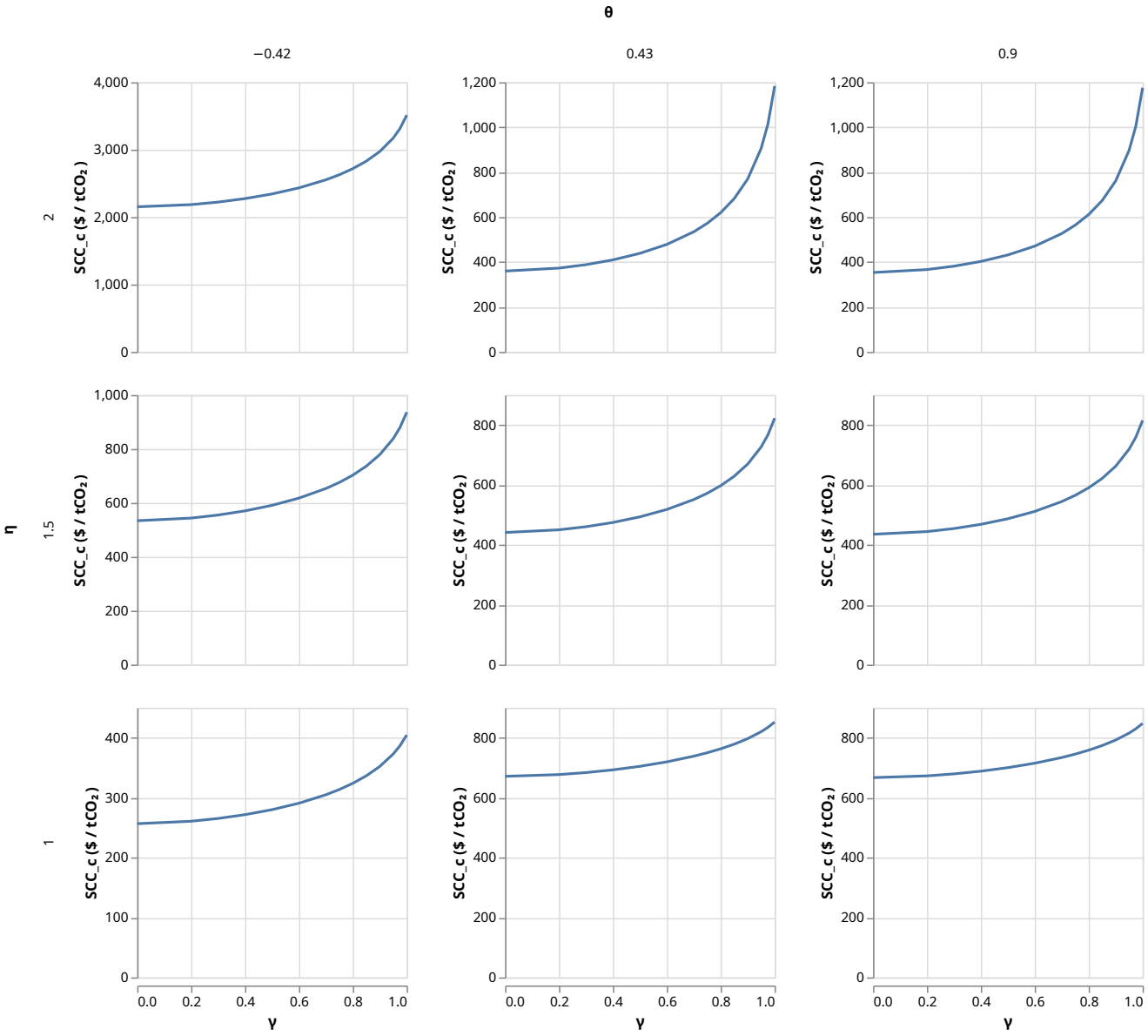


Figure A.3: Evolution of SCC_c with respect to national inequality γ, for different values of substitutability θ and inequality aversion η

Note: Columns represent increasing levels of substitutability θ. Rows show SCC_c under different levels of inequality aversion η.

Back to subsection 4.2

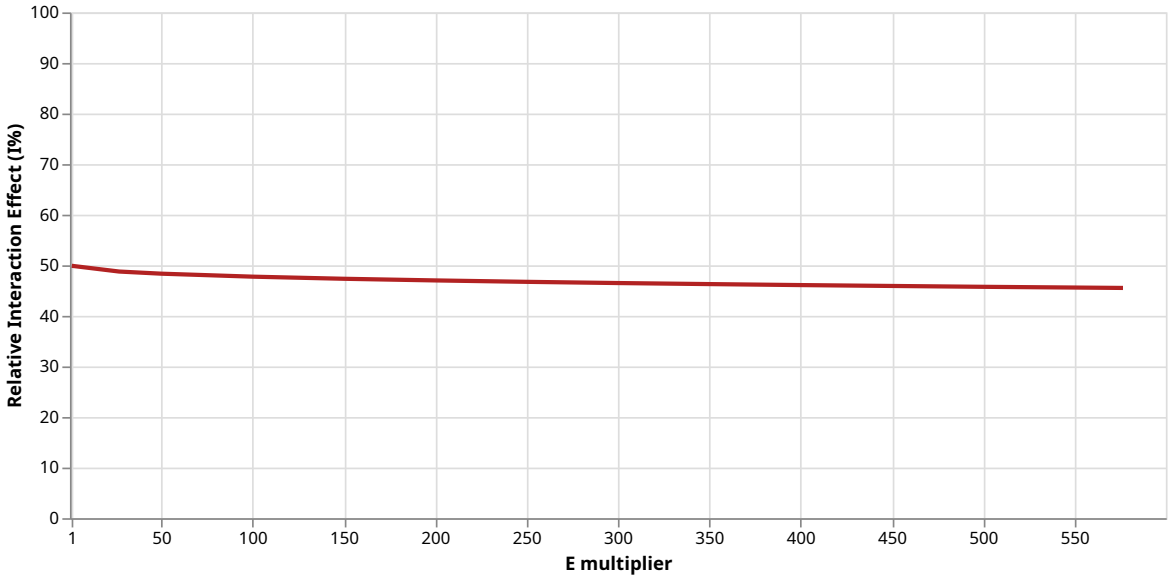


Figure A.4: Relative interaction effect $I_{\%}$ (in %) with respect to the initial flow of the non-market environmental good

Note: The red line shows how the aggregate relative interaction effect varies as the initial global flow of ecosystem services is multiplied by up to 577.

Back to subsection 4.3

B Relationship between the inequality coefficient and the standard deviation of national consumption

In country i, the variance of consumption is:

$$\begin{aligned}
\sigma_i^2 &= \frac{1}{n}\sum_{j=1}^{n}[c_i - c_{i,j}]^2 \\
&= \frac{1}{n}\sum_{j=1}^{n}[c_i - (1+\delta_{i,j}\gamma)c_i]^2 \\
&= \frac{1}{n}\sum_{j=1}^{n}[c_i - c_i - \delta_{i,j}\gamma c_i]^2 \\
&= \frac{1}{n}\sum_{j=1}^{n}[\delta_{i,j}\cdot\gamma c_i]^2 \\
&= \frac{1}{n}\sum_{j=1}^{n}\left[\frac{\hat{c}_{i,j}-c_i}{c_i}\cdot\gamma c_i\right]^2 \\
&= \frac{1}{n}\sum_{j=1}^{n}[(\hat{c}_{i,j}-c_i)\gamma]^2 \\
\sigma_i^2 &= \gamma^2\frac{1}{n}\sum_{j=1}^{n}(c_i-\hat{c}_{i,j})^2.
\end{aligned}$$

So:

$$\begin{aligned}
\sigma_i &= \gamma \times \sqrt{\frac{1}{n}\sum_{j=1}^{n}(c_i-\hat{c}_{i,j})^2} \\
&= \gamma \times \hat{\sigma}_i.
\end{aligned}$$

The standard deviation σ_i of country i's consumption distribution is the actual observed standard deviation $\hat{\sigma}_i = \sqrt{\frac{1}{n}(c_i-\hat{c}_{i,j})^2}$, multiplied by γ. In other words, inequality coefficient γ directly multiplies the baseline standard deviation of each country.

Back to subsection 2.1.

C Proof of proposition 1

Definitions

For tractability, we consider two income groups of size 1, with consumption c_1 and c_2. We define the consumption of the two groups as functions of average consumption $\bar{c}$ and inequality

coefficient γ:

$$\begin{cases} c_1 = \overline{c}\,(1-\gamma) \\ c_2 = \overline{c}\,(1+\gamma). \end{cases}$$

We define function v as the constant elasticity of substitution function that goes into the utility function:

$$v : c, E \longmapsto \left[(1-\alpha)c^{\theta} + \alpha E^{\theta}\right]^{1/\theta}.$$

Utility u and welfare W are defined as:

$$u : (c, E) \longmapsto \frac{v(c,E)^{1-\eta}}{1-\eta},$$
$$W : (\overline{c}, E) \longmapsto u(c_1, E) + u(c_2, E).$$

Expression of the cross derivative

Let us start by writing the cross derivative of welfare with respect to E and γ. For that, we first need the derivative of u with respect to E.

$$\begin{aligned} \forall c, E > 0, \quad \partial_2 v(c,E) &= \alpha\theta E^{\theta-1} \cdot \frac{1}{\theta}[(1-\alpha)c^{\theta} + \alpha E^{\theta}]^{(1-\theta)/\theta} \\ &= \alpha E^{\theta-1} \cdot v(c,E)^{1-\theta} \\ \partial_2 u(c,E) &= \alpha E^{\theta-1} v(c,E)^{1-\theta} \cdot \frac{1}{1-\eta} \cdot (1-\eta) v(c,E)^{1-\eta-1} \\ &= \alpha E^{\theta-1} v(c,E)^{1-\theta-\eta}. \end{aligned}$$

Now, the derivative of W with respect to E is:

$$\begin{aligned} \forall \overline{c}, E > 0, \quad \partial_2 W(\overline{c}, E) &= \partial_2 u(c_1, E) + \partial_2 u(c_2, E) \\ &= \alpha E^{\theta-1} v(c_1,E)^{1-\theta-\eta} + \alpha E^{\theta-1} v(c_2,E)^{1-\theta-\eta} \\ &= \alpha E^{\theta-1}\left[v(c_1,E)^{1-\theta-\eta} + v(c_2,E)^{1-\theta-\eta}\right]. \end{aligned}$$

We can now derive this expression with respect to γ. We start with the derivative of v.

$$\begin{aligned} \forall c > 0, \quad \partial_1 v(c,E) &= (1-\alpha)\theta c^{\theta-1} \cdot \frac{1}{\theta}[(1-\alpha)c^{\theta} + \alpha E^{\theta}]^{(1-\theta)/\theta} \\ &= (1-\alpha)c^{\theta-1} \cdot v(c,E)^{1-\theta}. \end{aligned}$$

Now:

$$\begin{aligned}
\forall \overline{c} > 0, \quad c_1 &= \overline{c}\,(1-\gamma) \qquad \text{and} \qquad c_2 = \overline{c}\,(1+\gamma) \\
c_1 &= \overline{c} - \overline{c}\,\gamma \qquad \text{and} \qquad c_2 = \overline{c} + \overline{c}\,\gamma \\
\partial_\gamma c_1 &= -\overline{c} \qquad \text{and} \qquad \partial_\gamma c_2 = \overline{c}.
\end{aligned}$$

So:

$$\begin{aligned}
\partial_\gamma v(c_1, E) &= \partial_\gamma c_1 \cdot \partial_1 v(c_1, E) \\
&= -\overline{c} \cdot (1-\alpha) c_1^{\theta-1} v(c_1, E)^{1-\theta}.
\end{aligned}$$

And likewise:

$$\partial_\gamma v(c_2, E) = \overline{c} \cdot (1-\alpha) c_2^{\theta-1} v(c_2, E)^{1-\theta}.$$

We can now derive the cross derivative:

$$\begin{aligned}
\partial^2_{E,\gamma} W &= \alpha E^{\theta-1}(1-\theta-\eta)\left[\partial_\gamma v(c_1, E) \cdot v(c_1, E)^{-\theta-\eta} + \partial_\gamma v(c_2, E) \cdot v(c_2, E)^{-\theta-\eta}\right] \\
&= \alpha E^{\theta-1}(1-\theta-\eta)\big[-\overline{c}(1-\alpha) c_1^{\theta-1} v(c_1, E)^{1-\theta} \cdot v(c_1, E)^{-\theta-\eta} \\
&\qquad + \overline{c}(1-\alpha) c_2^{\theta-1} v(c_2, E)^{1-\theta} \cdot v(c_2, E)^{-\theta-\eta}\big] \\
&= \overline{c}(1-\alpha)\alpha E^{\theta-1}(1-\theta-\eta)\left[c_2^{\theta-1} \cdot v(c_2, E)^{1-\eta-2\theta} - c_1^{\theta-1} \cdot v(c_1, E)^{1-\eta-2\theta}\right].
\end{aligned}$$

Sign of the cross derivative in different cases

Now that we have an expression for the cross derivative, we can study its sign. We can start by noticing that the first four factors, $\overline{c}(1-\alpha)\alpha E^{\theta-1}$, are all positive. Now, $1-\theta-\eta$ is positive if, and only if $\eta < 1-\theta$.

The sign of the expression between the square brackets is not obvious. To study it, let us define function f as:

$$f : c \longmapsto c^{\theta-1} v(c, E)^{1-\eta-2\theta}.$$

We know that for all $\gamma \in (0,1)$, $c_2 = c_1 + 2\gamma\overline{c}$ is greater than c_1. So, if f is decreasing, then

$$\begin{aligned}
f(c_2) &< f(c_1), \\
f(c_2) - f(c_1) &< 0,
\end{aligned}$$

and the expression between the square brackets is negative. In that case, the sign of $\partial^2_{E,\gamma} W$ is opposite to the sign of $1-\eta-\theta$. We will now show that f is decreasing for all θ and η such that $\eta > -\theta$. We will proceed by looking at different pieces of the (θ, η) plane, which we will

put together at the end. But first, let us take a closer look at function f. For all $c > 0$, we have:

$$\begin{aligned} f(c) &= c^{\theta-1} v(c,E)^{1-\eta-2\theta} \\ &= c^{\theta-1} \left[(1-\alpha)c^{\theta} + \alpha E^{\theta} \right]^{(1-\eta-2\theta)/\theta}. \end{aligned}$$

We can distribute $c^{\theta-1}$ inside the bracket, like so:

$$f(c) = \left[(1-\alpha)c^{\theta+(\theta-1)\theta/(1-\eta-2\theta)} + \alpha E^{\theta} c^{(\theta-1)\theta/(1-\eta-2\theta)} \right]^{(1-\eta-2\theta)/\theta}.$$

Simplifying the first inside exponent:

$$\begin{aligned} \theta + \frac{(\theta-1)\theta}{1-\eta-2\theta} &= \theta \left(1 + \frac{\theta-1}{1-\eta-2\theta} \right) \\ &= \theta \cdot \frac{1-\eta-2\theta+\theta-1}{1-\eta-2\theta} \\ &= \theta \cdot \frac{-\eta-\theta}{1-\eta-2\theta} \\ &= -(\eta+\theta) \cdot \frac{\theta}{1-\eta-2\theta}, \end{aligned}$$

we get:

$$f(c) = \left[(1-\alpha)c^{-(\eta+\theta)\cdot\theta/(1-\eta-2\theta)} + \alpha E^{\theta} c^{(\theta-1)\cdot\theta/(1-\eta-2\theta)} \right]^{(1-\eta-2\theta)/\theta}.$$

We will now study the sign of the three exponents in this function, in different cases. If the two exponents of c inside the bracket are of the same sign, then f is monotonous. Otherwise, the variation of f depends on its parameters, and f is not guaranteed to be monotonous.

Case 1: if $\dfrac{1-\eta-2\theta}{\theta} > 0$.

There are two ways for $\frac{1-\eta-2\theta}{\theta}$ to be positive. Either the numerator are both positive, or they are both negative.

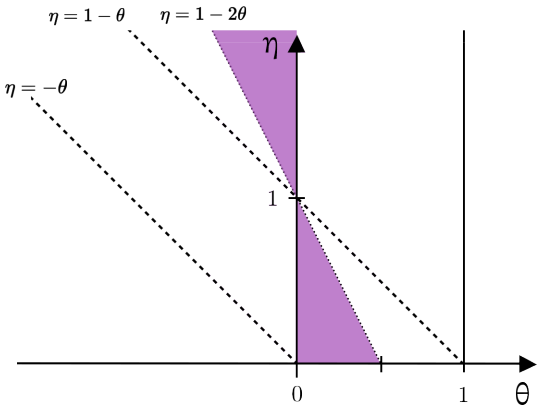


Figure A.5: Case 1 : $\frac{1-\eta-2\theta}{\theta} > 0$

In both cases, $\eta + \theta > 0$. Indeed:

$$\theta > 0 \Rightarrow \eta + \theta > \eta > 0,$$

and:

$$\begin{array}{lllll} & \theta < 0 & \text{and} & 1 - \eta - 2\theta < 0 \\ \Rightarrow & \theta < 1 & \text{and} & 1 - \theta < \eta + \theta \\ \Rightarrow & 0 < 1 - \theta & \text{and} & 1 - \theta < \eta + \theta \\ \Rightarrow & & 0 < \eta + \theta. & \end{array}$$

Because $\eta + \theta > 0$ and $\frac{1-\eta-2\theta}{\theta} > 0$, the first exponent is negative:

$$-(\eta + \theta) \cdot \frac{\theta}{1 - \eta - 2\theta} < 0.$$

Since, for all $\theta \in (-\infty, 1) \setminus \{0\}$, $\theta - 1$ is negative, the second exponent is also negative:

$$(\theta - 1) \cdot \frac{\theta}{1 - \eta - 2\theta} < 0.$$

So, both terms inside the brackets of function f are decreasing functions of c. Since $\frac{1-\eta-2\theta}{\theta} > 0$, the outside exponent is positive. So f is decreasing. We can conclude our first case: if $\frac{1-\eta-2\theta}{\theta} > 0$, then:

$$\text{sign}\left(\partial^2_{E,\gamma} W\right) = -\,\text{sign}\left(1 - \eta - \theta\right).$$

We now move to cases where $\frac{1-\eta-2\theta}{\theta}$ is negative. There are two ways for $\frac{1-\eta-2\theta}{\theta}$ to be negative. Either the numerator is negative and the denominator is positive, or the reverse. We start with

the case where the numerator is negative.

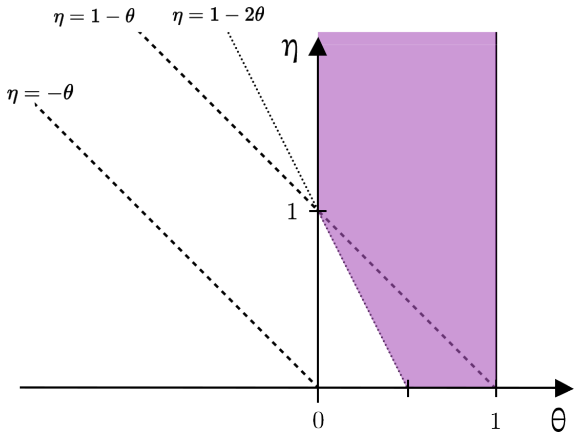
Case 2: if $1-\eta-2\theta<0$ and $\theta>0$.

If $1-\eta-2\theta<0$ and $\theta>0$, then $\frac{1-\eta-2\theta}{\theta}$ is negative. We also have:

$$1-\eta-2\theta<0$$
$$1-\theta<\eta+\theta.$$

Now, $\theta\leq 1$, so $0\leq 1-\theta$. Therefore:

$$\eta+\theta>0.$$



Case 2 : $1-\eta-2\theta<0$ and $\theta>0$

We can now look at the different exponents of function f. We have:

$$-(\eta+\theta)\frac{1-\eta-2\theta}{\theta}>0$$

and

$$(\theta-1)\frac{1-\eta-2\theta}{\theta}>0.$$

So, function

$$c\longmapsto(1-\alpha)c^{-(\eta+\theta)\cdot\theta/(1-\eta-2\theta)}+\alpha E^{\theta}c^{(\theta-1)\cdot\theta/(1-\eta-2\theta)}$$

is increasing. It becomes decreasing when raised to the power $(1-\eta-2\theta)/\theta<0$. So function f is decreasing. We can now conclude case 2: if $1-\eta-2\theta<0$ and $\theta>0$, then $\operatorname{sign}\left(\partial^2_{E,\gamma}W\right)=-\operatorname{sign}(1-\eta-\theta)$.

Case 3: if $1-\eta-2\theta>0$, $\theta<0$, and $\eta+\theta>0$.

If $1-\eta-2\theta>0$, $\theta<0$, and $\eta+\theta>0$, then:

$$-(\eta+\theta)\frac{\theta}{1-\eta-2\theta}>0,$$

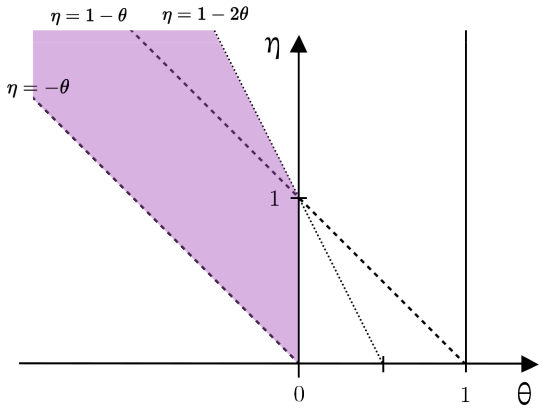
and:

$$(\theta-1)\frac{\theta}{1-\eta-2\theta}>0.$$

So, function

$$c \longmapsto (1-\alpha)c^{-(\eta+\theta)\cdot\theta/(1-\eta-2\theta)} + \alpha E^{\theta} c^{(\theta-1)\cdot\theta/(1-\eta-2\theta)}$$

is increasing. It becomes decreasing when raised to the power $(1-\eta-2\theta)/\theta < 0$. So function f is decreasing. Case 3 concludes just like the two previous cases: if $1-\eta-2\theta < 0$, $\theta > 0$, and $\eta+\theta > 0$, then $\operatorname{sign}\left(\partial^2_{E,\gamma} W\right) = -\operatorname{sign}(1-\eta-\theta)$.



Case 3 : $1-\eta-2\theta > 0$, $\theta < 0$, and $\eta+\theta > 0$

Case 4: if $1-\eta-2\theta > 0$, $\theta < 0$, and $\eta+\theta < 0$.

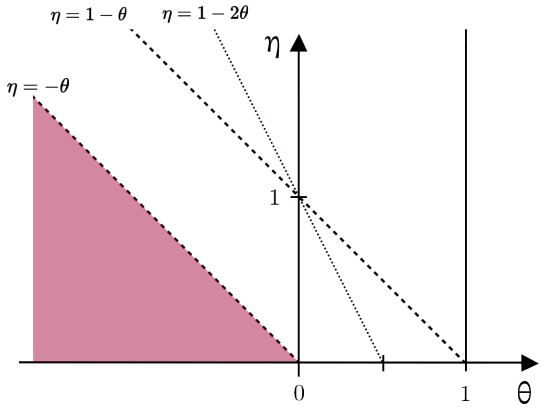
If $1-\eta-2\theta > 0$, $\theta < 0$, and $\eta+\theta < 0$, then:

$$-(\eta+\theta)\frac{\theta}{1-\eta-2\theta} < 0,$$

and:

$$(\theta-1)\frac{\theta}{1-\eta-2\theta} > 0.$$

Since the two exponents of c are of opposite signs, the variation of f is ambiguous.



Case 4 : $1-\eta-2\theta > 0$, $\theta < 0$, and $\eta+\theta < 0$.

Conclusion

Taken together, cases 1, 2 and 3 cover the part of the (η, θ) plane where η is greater than $-\theta$. Since the three cases have the same conclusion, we can say that on the domain they cover, the sign of the cross derivative of welfare is opposite to the sign of $1 - \eta - \theta$:

$$\forall \theta < 1,\ \forall \eta > \max\{-\theta, 0\},\ \operatorname{sign}\left(\partial^2_{E,\gamma} W\right) = -\operatorname{sign}\left(1 - \eta - \theta\right).$$

Back to proposition 1.

D Countries used as input for for natural capital missing values

Table 1: Countries used as input for natural capital missing values

Country with missing N		Input country	
ISO3	Country	ISO3	Country
ABW	Aruba	MLT	Malta
AFG	Afghanistan	TJK	Tajikistan
BHS	Bahamas	JAM	Jamaica
BRB	Barbados	SLB	Solomon Is.
BRN	Brunei	SGP	Singapore
BTN	Bhutan	NPL	Nepal
CPV	Cabo Verde	MUS	Mauritius
CUB	Cuba	DOM	Dominican Rep.
CYP	Cyprus	MLT	Malta
DZA	Algeria	NER	Niger
ERI	Eritrea	OMN	Oman
FJI	Fiji	SLB	Solomon Is.
GNQ	Eq. Guinea	BEN	Benin
HKG	Hong Kong	SGP	Singapore
LBY	Libya	EGY	Egypt
MMR	Myanmar	THA	Thailand
PSE	Palestine	JOR	Jordan
PYF	Fr. Polynesia	SLB	Solomon Is.
SYR	Syria	IRQ	Iraq
TKM	Turkmenistan	KAZ	Kazakhstan
TLS	Timor-Leste	SLB	Solomon Is.
TON	Tonga	SLB	Solomon Is.
TWN	Taiwan	KOR	South Korea
UZB	Uzbekistan	KAZ	Kazakhstan
VCT	St. Vincent & Gren.	SLB	Solomon Is.
VUT	Vanuatu	SLB	Solomon Is.
WSM	Samoa	SLB	Solomon Is.
YEM	Yemen	SAU	Saudi Arabia

Note: Initial natural capital for countries not included in CWON is assigned based on geographic proximity and similarity in forest area. For small island states, the initial natural capital stock is set equal to that of an island of comparable size.

Back to subsection 3.1

E Countries used as input for damage coefficient missing values

Table 2: Countries used as input for missing damage coefficient values

Country with missing ξ		Input country	
ISO3	Country	ISO3	Country
ABW	Aruba	DOM	Dominican Rep.
AFG	Afghanistan	TJK	Tajikistan
AGO	Angola	COD	Congo, Dem. Rep.
BHR	Bahrain	QAT	Qatar
BHS	Bahamas	JAM	Jamaica
BRB	Barbados	DOM	Dominican Rep.
BRN	Brunei	IDN	Indonesia
BTN	Bhutan	NPL	Nepal
COM	Comoros	MDG	Madagascar
CPV	Cabo Verde	MDG	Madagascar
CUB	Cuba	DOM	Dominican Rep.
CYP	Cyprus	TUR	Turkey
DZA	Algeria	NER	Niger
ERI	Eritrea	OMN	Oman
FJI	Fiji	SLB	Solomon Is.
GNB	Guinea-Bissau	GIN	Guinea
GNQ	Eq. Guinea	BEN	Benin
HKG	Hong Kong	CHN	China
ISR	Israel	JOR	Jordan
LBY	Libya	EGY	Egypt
LCA	St. Lucia	DOM	Dominican Rep.
MAC	Macao	CHN	China
MDV	Maldives	LKA	Sri Lanka
MLT	Malta	ITA	Italy
MMR	Myanmar	THA	Thailand
MNE	Montenegro	ALB	Albania
MUS	Mauritius	MDG	Madagascar
NZL	New Zealand	AUS	Australia
PSE	Palestine	JOR	Jordan
PYF	Fr. Polynesia	SLB	Solomon Is.
SDN	Sudan	TCD	Chad
SGP	Singapore	MYS	Malaysia
SRB	Serbia	HRV	Croatia
STP	São Tomé & Príncipe	GAB	Gabon
SYR	Syria	IRQ	Iraq
TKM	Turkmenistan	KAZ	Kazakhstan
TLS	Timor-Leste	SLB	Solomon Is.
TON	Tonga	SLB	Solomon Is.
TWN	Taiwan	KOR	South Korea
UZB	Uzbekistan	KAZ	Kazakhstan
VCT	St. Vincent & Gren.	SLB	Solomon Is.
VUT	Vanuatu	SLB	Solomon Is.
WSM	Samoa	SLB	Solomon Is.

Note: The criteria used are as follows. First, keep input criteria for N. Second, input the damage coefficient from the closest country. Third, assign the Dominican Republic damage coefficient for the remaining island states.

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F Converting a stock of natural capital to a flow of ecosystem services

The Common Wealth Of Nations database gives a *stock* of natural capital for each country. This stock is obtained by aggregating a flow of ecosystem services over time, as explained by equation 6 of the CWON report (World Bank 2024, chapter 7, p. 145). Adapting this equation to our notation, the formula is:

$$N = \sum_{t=1}^{100} \frac{E}{(1+r)^t},$$

where N is the present value of ecosystem services, E is the yearly flow, and r is a 4% discount rate. To recover the value of constant E, we start by factorizing it:

$$N = E \sum_{t=1}^{100} \frac{1}{(1+r)^t}.$$

Using the formula for geometric sums, we can write:

$$N = E \cdot \frac{1}{1+r} \cdot \frac{1 - \left(\frac{1}{1+r}\right)^{100}}{1 - \frac{1}{1+r}}.$$

The second denominator simplifies:

$$\begin{aligned} 1 - \frac{1}{1+r} &= \frac{1+r-1}{1+r} \\ &= \frac{r}{1+r}. \end{aligned}$$

So:

$$\begin{aligned} N &= E \cdot \frac{1}{1+r} \cdot \frac{1 - \left(\frac{1}{1+r}\right)^{100}}{\frac{r}{1+r}} \\ &= E \cdot \frac{1}{1+r} \cdot \frac{1+r}{r} \cdot \left(1 - \left(\frac{1}{1+r}\right)^{100}\right) \\ &= E \cdot \frac{1}{r} \cdot \left(1 - (1+r)^{-100}\right). \end{aligned}$$

We can now express E as a function of N:

$$E = N \cdot \frac{r}{1 - (1+r)^{-100}}.$$

Replacing r by its value gives us the stock-to-flow conversion factor:

$$E = N \cdot \frac{0.04}{1 - (1 + 0.04)^{-100}}$$

$$E \approx N \cdot 0.040808.$$

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