- c: Country
- t: Time
- $b = \{\text{corals}, \text{mangroves}\}$ and $v = \{\text{non-market use}, \text{non-use}\}$
- $p_{c,t}$ is the annual per-area value 2005 USD per km^2 comes Brander et al (2024).
- $A^b_{c,t}$: Area of marine biome [km^2] from UNEP World Conservation Monitoring Centre
- T: Global mean temperature
- ΔT: Global mean temperature anomaly since pre-industrial times
- $V^{b,v}_{c,t}$: Annual total values [2005 USD per year]

Corals

Non-market use and non-use

$$p^{coral,v}_{c,t+1} = p^{coral,v}_{c,t} \cdot \left(1 + \gamma^v \cdot GDPpc\ growth_{c,t}\right) \tag{1}$$
$$A^{coral}_{c,t} = A^{coral}_{c,0} \cdot (1 + \delta^{coral}_c \cdot \Delta T_t) \tag{2}$$
$$V^{coral,v}_{c,t} = p^{coral,v}_{c,t} \cdot A^{coral}_{c,t} \tag{3}$$

γ^v comes from. Brander et al (2024). Area damage coefficient δ^{coral}_c are estimated as follows:

1. Projected changes in coral area at 2,949 sites for 2050 and 2100, RCP 4.5, 8.5, from Sully et al
2. Estimate damage coefficient for each site: $A_{(i)t} = \alpha + \delta^{coral}_i \Delta GMST_t + \epsilon_t \quad \forall i$
3. Assign a δ^{coral}_i to all corals reefs, based on nearest sites.
4. Coral-area-weighted average damage coefficient δ^{coral}_c for each country $\delta^{coral}_c = \sum_{i(c)} \dfrac{A_{i(c)} \cdot \delta^{coral}_{i(c)}}{\sum_{i(c)} A_i(c)}$
5. The uncertainty around δ^{coral}_c is given by σ_{δ_c}, the square root of coral-area-weighted average variance of δ^{coral}_i. $\sigma^{2\ coral}_c = \sum_{i(c)} \left(\frac{A_{i(c)}}{\sum_{i(c)} A_i(c)}\right)^2 \cdot \sigma^{2\ coral}_{i(c)}$.

Market use

Market damage coefficient $\lambda^{coral}_{1,c}$ is estimated fitting separately for each country

$$D^{coral}_t = \lambda^{coral}_1 \Delta T_t + \epsilon_t \quad \forall c$$

with damages being the value of corals with and without damages:

$$D^{coral}_{c,t} = p^{coral}_{c,t} \cdot (A^{coral}_{c,t} - A^{coral}_{c,0}).$$

Uncertainty

Call $\sigma_{\lambda^{coral}_1}$ the standard error of λ^{coral}_1. The adjusted variance of $\lambda^{coral}_{1,c}$ is ... ..

Mangroves

Non-market use and non-use

$$p^{mangroves,v}_{c,t} = e^{a^v_c} \cdot GDPpc^{b^v_c}_{c,t} \tag{4}$$
$$A^{mangroves}_{c,t} = A^{mangroves}_{c,0} \cdot (1 + \delta^{mangroves}_{1,c} \cdot \Delta T_t + \delta^{mangroves}_{2,c} \cdot \Delta T^2_t) \tag{5}$$
$$V^{mangroves,v}_{c,t} = p^{mangroves,v}_{c,t} \cdot A^{mangroves}_{c,t} \tag{6}$$

- a^v_c and b^v_c estimated fitting $\quad p^{mangroves,v}_t = e^{a^v} \cdot GDPpc^{c^v}_t + \varepsilon_t \quad \forall c$
- $\delta_{1,c}$ and $\delta_{2,c}$ from Bastien-Olvera et al. (In Prep.)

Market use

Market damage coefficients $\lambda_{1,c}^{mangroves}$ and $\lambda_{2,c}^{mangroves}$ are estimated fitting

$$D_{c,t}^{mangroves} = \lambda_{1,c}^{mangroves} \Delta T_t + \lambda_{2,c}^{mangroves} \Delta T_t^2 + \epsilon_{c,t}$$

where

$$D_{c,t}^{mangroves} = p_{c,t}^{mangroves,v} \cdot (A_{c,t}^{mangroves} - A_{c,0}^{mangroves}) \cdot GDP_{c,t}$$

Uncertainty

Call σ_D the standard deviation of

Fisheries

$$Health\ benefits_{c,t} = (1 + \beta_c T_t) \cdot TAME \cdot Pop_{c,t} \cdot \mu_c \cdot \eta \cdot VSL_t$$

Where η is the percentage of nutrient intake that cannot be made up by consuming other foods, μ_c thr percentage of population in country c dependent on fisheries, and $TAME_c$ is the total avoided mortality effect of country c, defined as the sum of the baseline mortality rate (MR) associated with health condition h, times the protective effect ρ that each nutrient n has on such condition:

$$TAME_c = \sum_{(n,h) \in M} \rho_{n,h} \cdot MR_{c,h,2020}$$

M is the set of specific pairs (n, h) for which we have values in our meta-analysis dataset. The Value of a Statistical Life (VSL) is uniform across countries and it changes across time, following recommendations by Bressler and Heal. We scaled the VSL using the global population-weighted mean GDP per capita:

$$VSL_t = \widetilde{VSL}_t \cdot \frac{Global\ GDPpc_t}{Global\ GDPpc_{2020}}.$$

$\widetilde{VSL}_t$ is the VSL estimate currently used by the U.S. Environment Protection Agency, which fits a Weibull distribution to 26 studies with a central value of $7.4 million (2006 USD), and a standard deviation of $4.7 million (2006 USD).

Market use

Free et al. (2020) projects national profits from fisheries at full adaptation for 4 RCPs until 2100 at 5-year intervals [CHECK]. We compare the difference in profits from RCP2.6 and the deviation in GMT from RCP2.6, summarizing the relationship between economic damages and climate change with a linear relation, separately for each country. We do so fitting the following line:

$$D_t^{fisheries} = \alpha + \lambda_{1,c}^{fisheries} \underset{RCP2.6}{\Delta T_t} + \varepsilon_t \quad \forall c$$

with $D_t^{fisheries} = Profits_{t,RCP\neq 2.6} - Profits_{t,RCP2.6}$.

Ports

Verschuur et al project the economic value at risk (EVaR) for 7 SSP-RCP scenarios in 2050. We compute change since today in economic value at risk (EVaR) as a fraction of GDP

$$D_{c,t}^{ports} = \frac{EVaR_{c,t}}{GDP_{c,t}} - \frac{EVaR_{c,0}}{GDP_{c,0}}.$$

We summarize the relationship between economic damages on ports and climate change with a linear relation that passes through the origin, separately for each country:

$$D_t^{ports} = \lambda_{1,c}^{ports} \Delta T_t + \varepsilon_t \quad \forall c$$

Consumption

$$C_{c,t} = \widetilde{C}_{c,t} \cdot \big[(1 + \lambda_{1,c}^{coral} + \lambda_{1,c}^{mangrove} + \lambda_{1,c}^{fish} + \lambda_{1,c}^{port}) \cdot \Delta T_t + (1 + \lambda_{2,c}^{mangrove}) \cdot \Delta T_t^2\big] \tag{7}$$

where $\widetilde{C}_{c,t}$ is consumption absent climate change damages to the ocean ecosystems.

Utility

$$Utility_{c,t} = \left[(1-s_2)\cdot \text{Use}_{t,n}^{\theta_2} + s_2 \cdot \text{Non-use}^{\theta_2}\right]^{\frac{1}{\theta_2}} \tag{8}$$

where

$$\text{Use}_{t,n} = \left[(1-s_1)\cdot \widetilde{C}_{t,n}^{\theta_1} + s_1 \cdot \left(\sum_{b=m,c,f} V_{t,n}^{b,\text{non-mkt use}}\right)^{\theta_1}\right]^{\frac{1}{\theta_1}}$$

and

$$\text{Non-Use}_{t,n} = \sum_{b=m,c} (V_{t,n}^{b,\text{non-use}})$$

Social cost of carbon

We compute the Social Cost of Carbon from oceans based on the nested welfare function and separate it by the different categories and types of services $V_{c,t}^{b,v}$, based on the instantaneous utility function $U_{c,t}(c_{c,t}, V_{c,t}^{b,v})$ and intertemporal welfare function $W_c = \sum_{t=2020}^{2300} \frac{1}{1-\eta} U_{c,t}^{1-\eta}$. We run the model once (all variables denoted without hat) and then a second time adding one additional pulse of $1MtCO2$ of emissions in 2020. First we compute the monetary-equivalent utility impact at any time t and in country i by computing for each combination of b and v

$$\Delta U_{c,t}^{b,v} = \frac{1}{1-\eta} \cdot (U_{b,v,pulse,c,t}^{1-\eta} - U_{b,v,nopulse,c,t}^{1-\eta}),$$

that is, the difference in utility due to a change only due to impacts on $V_{c,t}^{b,v}$, whereas all other variables are kept at levels of the model run without emission pulse. This utility loss is then converted into monetary equivalents by the marginal utility of one unit of consumption $\frac{\partial U_{c,t}(c_{c,t}, V_{c,t}^{b,v})}{\partial c_{c,t}}$. Finally, we use the endogenous global Ramsey discount factor as for instance in Rennert et al. (2022), which in our case can be computed as $DF_t = (1+\delta)^{-(t-2020)} \frac{\left(\sum_c \frac{l_{c,t}}{\sum_{c'} l_{c',t}} c_{c,t}\right)^{-\eta}}{\left(\sum_c \frac{l_{c,2020}}{\sum_{c'} l_{c',2020}} c_{c,2020}\right)^{-\eta}}$. Thus, we can compute the Social Cost of Carbon for 2020 in US-$[2020] based on the sum of the disaggregated impacts as

$$SCC_{2020}^{OCEAN} = \sum_{t=2020}^{2300} (1+\delta)^{-(t-2020)} \frac{\left(\sum_c \frac{pop_{c,t}}{\sum_{c'} pop_{c',t}} c_{c,t}\right)^{-\eta}}{\left(\sum_c \frac{pop_{c,2020}}{\sum_{c'} pop_{c',2020}} c_{c,2020}\right)^{-\eta}} \left[\sum_c \frac{\sum_{b,v} \Delta U_{c,t}^{b,v}}{\frac{\partial U_{c,t}(c_{c,t}, V_{c,t}^{b,v})}{\partial c_{c,t}}} \cdot \frac{pop_{c,t}}{\sum_c pop_{c',t}}\right] \cdot \sum_c pop_{c,t}.$$

The sum of the contributions adds to the total utility difference. As an additional test, we also ran a grid of carbon prices verifying that the welfare levels are maximized at the level of the SCC obtained.

For internal use

Subscripts omitted for readiblity.

$$Utility = \frac{\left(\left((1-s_2)\left((1-s_1)C^{\theta_1} + Q^{\theta_1}s_1\right)^{\frac{\theta_2}{\theta_1}} + Z^{\theta_2}s_2\right)^{\frac{1}{\theta_2}}\right)^{1-\eta}}{1-\eta}$$

$$\frac{\partial U}{\partial C} = \frac{(1-s_1)(1-s_2)C^{\theta_1-1}\cdot\left((1-s_1)C^{\theta_1} + Q^{\theta_1}s_1\right)^{\frac{\theta_2}{\theta_1}-1}\left(\left((1-s_2)\left((1-s_1)C^{\theta_1} + Q^{\theta_1}s_1\right)^{\frac{\theta_2}{\theta_1}} + Z^{\theta_2}s_2\right)^{\frac{1}{\theta_2}}\right)^{1-\eta}}{(1-s_2)\left((1-s_1)C^{\theta_1} + Q^{\theta_1}s_1\right)^{\frac{\theta_2}{\theta_1}} + Z^{\theta_2}s_2}$$

with $Q = \sum_{b,v} = V^{b,nonmkt}$ and $Z = \sum_{b,v} = V^{b,nonuse}$