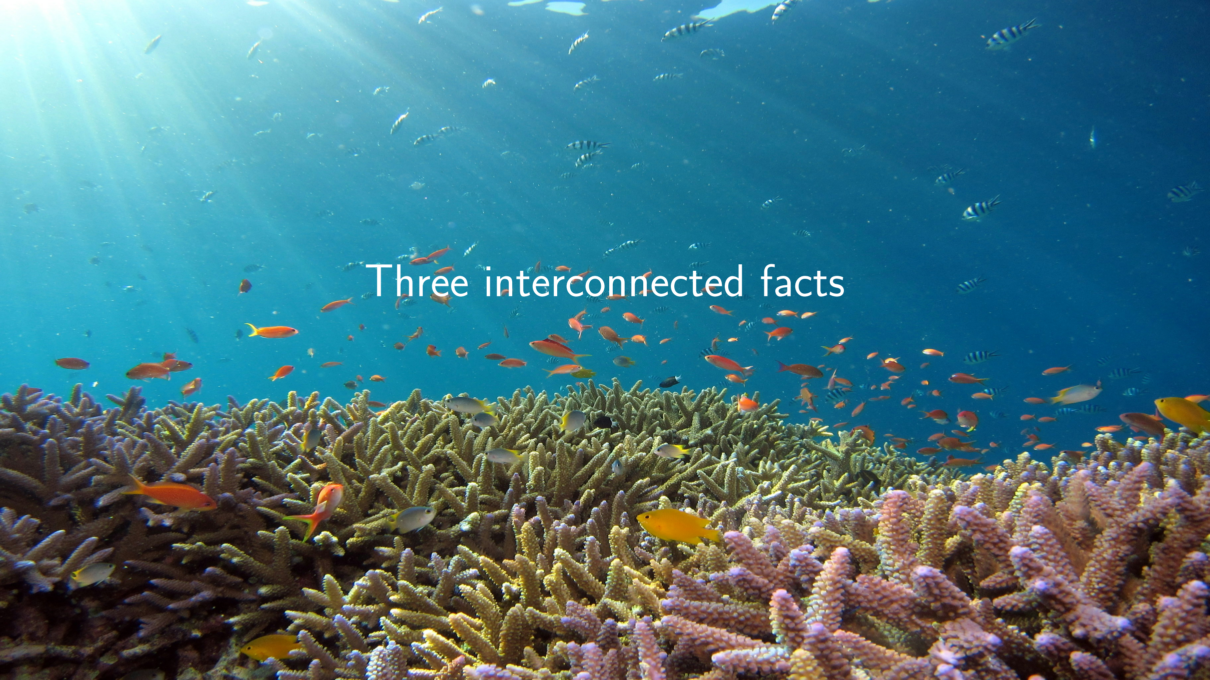
# The Social Cost of Carbon for the Oceans

Francesco Granella, CMCC

with Bernardo Bastien-Olvera, Ocatvio Aburto-Oropeza, Luke Brander, William Cheung, Johannes Emmerling, Chris Free, Massimo Tavoni, Jasper Verschuur, Kate Ricke

June 17, 2025

Funded under the Horizon Europe project n. 101081369 SPARCCLE



# Three interconnected facts

# The Climate-Ocean-Economy Nexus

1. Ocean economies are large
    - Oceans are backbone of global trade (Verschuur et al. 2023)
    - Essential market and non-market benefits
    - In many low-income countries, irreplaceable source of nutrition (Cheung et al. 2024)
    - ..and many others forms of benefits

# The Climate-Ocean-Economy Nexus

1. Ocean economies are large
    - Oceans are backbone of global trade (Verschuur et al. 2023)
    - Essential market and non-market benefits
    - In many low-income countries, irreplaceable source of nutrition (Cheung et al. 2024)
    - ..and many others forms of benefits

2. Climate change has impacts on oceans
    - Ocean chemistry, coral bleaching, species shifts, coastal erosion..

# The Climate-Ocean-Economy Nexus

1. Ocean economies are large
   - Oceans are backbone of global trade (Verschuur et al. 2023)
   - Essential market and non-market benefits
   - In many low-income countries, irreplaceable source of nutrition (Cheung et al. 2024)
   - ..and many others forms of benefits

2. Climate change has impacts on oceans
   - Ocean chemistry, coral bleaching, species shifts, coastal erosion..

3. Climate-economy models largely ignore ocean damages
   - U.S. National Academy of Sciences (2017) calls for ocean integration
   - EPA (2023) acknowledges ocean impacts missing from SCC
   - Current models exclude fisheries, coral services, coastal ecosystems

# The Climate-Ocean-Economy Nexus

1. Ocean economies are large
   - Oceans are backbone of global trade (Verschuur et al. 2023)
   - Essential market and non-market benefits
   - In many low-income countries, irreplaceable source of nutrition (Cheung et al. 2024)
   - ..and many others forms of benefits

2. Climate change has impacts on oceans
   - Ocean chemistry, coral bleaching, species shifts, coastal erosion..

3. Climate-economy models largely ignore ocean damages
   - U.S. National Academy of Sciences (2017) calls for ocean integration
   - EPA (2023) acknowledges ocean impacts missing from SCC
   - Current models exclude fisheries, coral services, coastal ecosystems

**Current estimates of the Social Cost of Carbon (SCC)**
**are missing a big part of the story**

# This paper

## Central question

What is the social cost of carbon when we account for climate impacts on the oceans?

# This paper

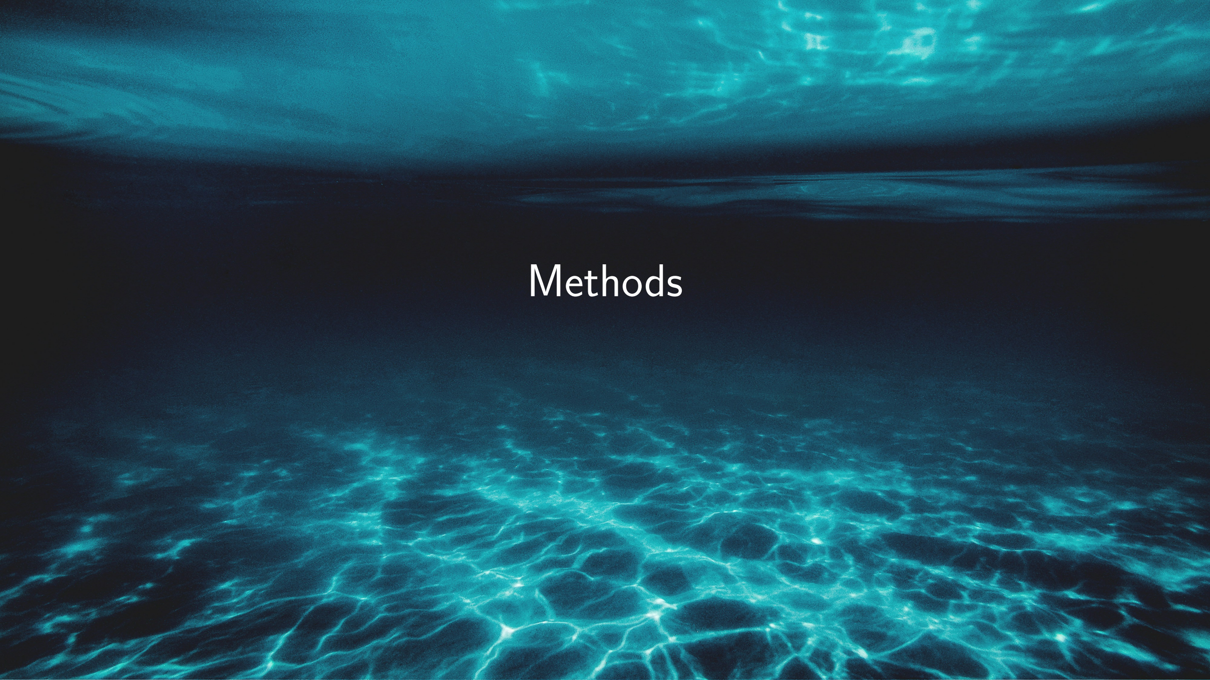
## Central question

What is the social cost of carbon when we account for climate impacts on the oceans?

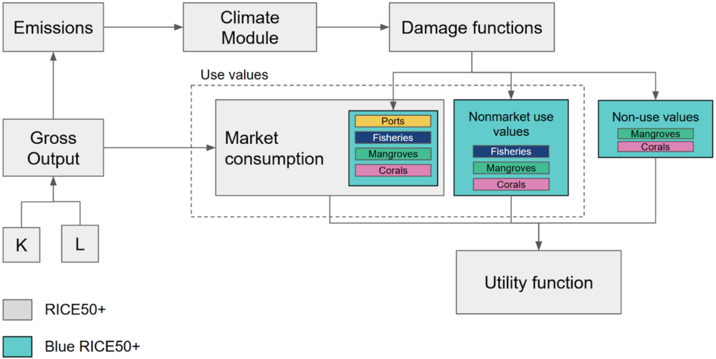
## Our Approach

- Develop ocean-specific damage functions
- 4 types of "blue capital": corals, mangroves, fisheries/mariculture, seaports
- Integrate these into the RICE50+ Integrated Assessment Model (IAM)
- Nested utility function with **market and non-market values**

# Methods



# The *Blue* RICE50+ Model




- CBA Climate-economy model with 155 regions
- Region-level ocean-specific damage functions

# The Utility Function

$$Utility_{c,t} = \left[s_{1,1} \cdot Use_{c,t}^{\theta_2} + s_{1,2} \cdot Nonuse_{c,t}^{\theta_2}\right]^{1/\theta_2}$$

Where:

$$Use_{c,t} = \left[s_{2,1} \cdot \boxed{C_{t,c}^{\theta_1}} + s_{2,2} \cdot \left(\sum_{b=mangroves,coral,fisheries} \boxed{V_{c,t}^{b,nonmarket\ \ use}}\right)^{\theta_1}\right]^{\frac{1}{\theta_1}}$$

$$Nonuse_{c,t} = \sum_{b=mangroves,coral} \boxed{V_{c,t}^{b,nonuse}}$$

- $\theta_1, \theta_2 = 0.21$: **limited substitutability** between value types (Drupp et al., 2024): You can't replace coral reefs with manufactured goods
- Country-specific ($c$) and time-varying ($t$)
- Climate affects consumption ($C_{c,t}$) and non-market values ($V_{c,t}^{b}$)

# Four Types of Blue Capital

| | Market use values | Non-market use values | Non-use values |
|---|---|---|---|
| Corals | Brander et al 2024, Sully et al 2022 | Brander et al 2024, Sully et al 2022 | Brander et al 2024, Sully et al 2022 |
| Mangroves | Brander et al 2024, B-O et al | Brander et al 2024, B-O et al | Brander et al 2024, B-O et al |
| Fisheries | Profits, Free et al (2020) | Nutrition, Cheung et al 2023 | |
| Ports | Econ value at risk, Verschuur et al 2022 | | |

We build damage functions

$$Value_{c,t}^{b,v} = f_c^{b,v}(\Delta GMT_t)$$

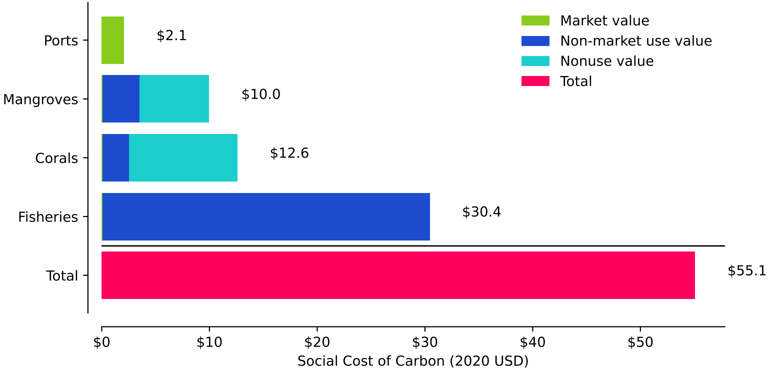
for each blue capital $b$, type of value $v$ and country $c$.

Details: Corals Mangroves Fisheries Ports

# The Social Cost of Carbon for the Oceans

## Results and robustness

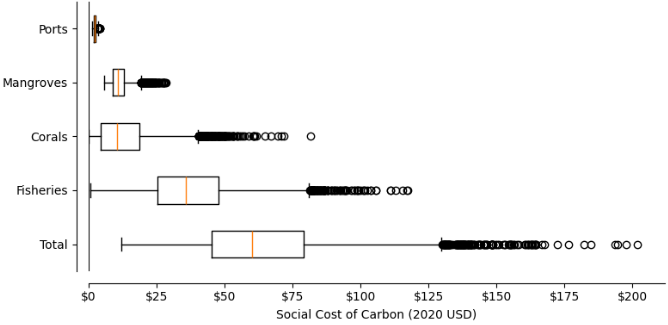
# The Social Cost of Carbon for the Oceans




$55 per ton of $CO_2$ in 2020, approx 29% of US government's SCC.

# Uncertainty over the SCC

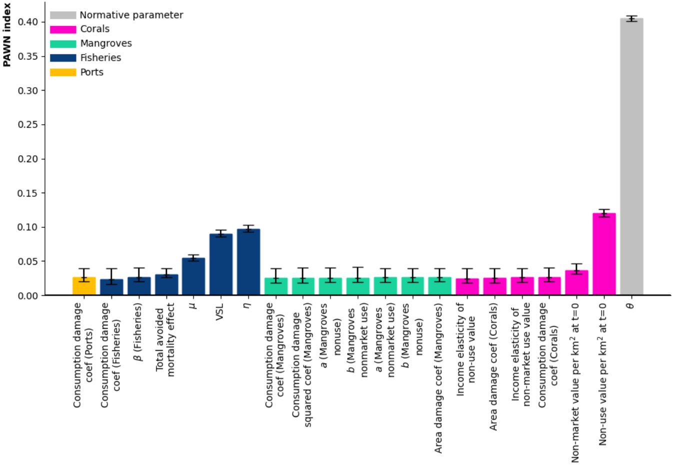
- 10.000 random draws with Latin Hypercube Sampling for effiecient exploration of parameter space
- 25 parameters, including climate sisnitivity, PRTP, elasticity of substitution
- 25th-75th percentiles: \$45-\$79/$tCO_2$



# Global sensitivity analysis

- PAWN index (Pianosi and Wagener, 2015) More on PAWN index
  Moment-independent global sensitivity analysis method that measures input parameter influence on model output

- Substitutability parameter $\theta$ drives variation in SCC



# Conclusions

## Ocean damages are economically significant and socially urgent

1. SCC-O at \$55/$tCO_2$, 29% increase over EPA's 2024 SCC
    - Comparable to agriculture (\$84) or mortality (\$90) damages (Rennert et al. 2022)
    - Robust across scenarios [IQR: \$45-\$75]
2. Non-market values dominate (83%)
    - Nutrition security, coastal protection, etc.
    - Markets miss what matters most for welfare
3. Profound inequities
    - Small Islands & LDCs face disproportionate losses
    - Those least responsible suffer most

Thank you

francesco.granella@cmcc.it

# Damage functions

# Corals

$$Value_{c,t}^{corals,v} = Value\_km2_{c,t}^{corals,v} \cdot Area_{c,t}^{corals}$$

1. Value of a km2 of coral reefs (Brander et al., 2024) (Market use, Non-market use, Non-use)
2. Biophysical changes of coral reefs area with increases in temperature (based on Sully et al. (2022))

# Building damage functions

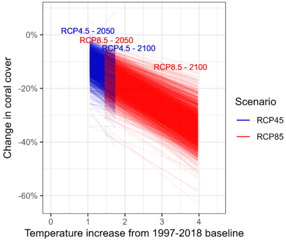
## Values

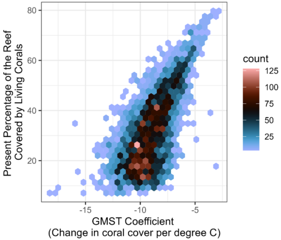
Use and non-use values from Corals from Brander et al. (2024)

- Market use values: Food, raw materials, ornamental resources (\$19,289/ha/year)
- Non-market use values: Climate regulation, moderation of extreme events, waster treatment, erosion prevention, maintenance of soil (\$36,186/ha/year)
- Nonuse values: Maintenance of lifecycles, of genetic diversity, existence value, bequest value (\$29,610/ha/year)
- Income elasticity: Values increase with GDP per capita ($\gamma = 0.13$-$0.24$)

# Building damage functions

## Biophysical changes




Coral cover damage as a function of global mean surface temperature

- Temperature stress $\rightarrow$ coral bleaching and mortality
- Coral area damage coefficients $\delta_c^{coral}$ from Sully et al. (2022) for 2,949 sites

Back

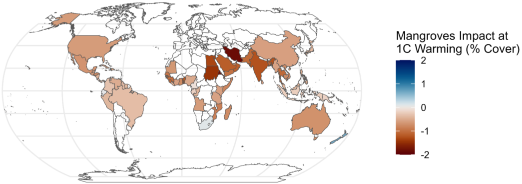
# Mangroves

$$Value_{c,t}^{mangroves,v} = Value\_km2_{c,t}^{mangroves,v} \cdot Area_{c,t}^{mangroves}$$

1. Value of a km2 of mangrove forests (Brander et al., 2024) (Market use, Non-market use, Non-use)
2. Biophysical changes of mangrove forests area with increases in temperature (based on Bastien-Olvera et al., In Prep.)

# Mangroves

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




- $p^{mangroves,v}_{c,t}$ from Brander et al. (2024)
- $\delta_{1,c}$ and $\delta_{2,c}$ from Bastien-Olvera et al. (In Prep.)

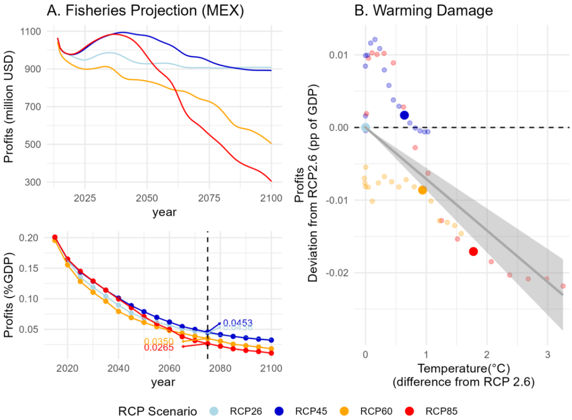
Back

# Fisheries

1. Market values: Direct GDP impacts through consumption (based on Free et al. (2020))
2. Non-market use values: Health benefits from nutrition, not traded in markets (own calculations, based on Cheung et al. (2023))

# Fisheries

## Market Damage Function

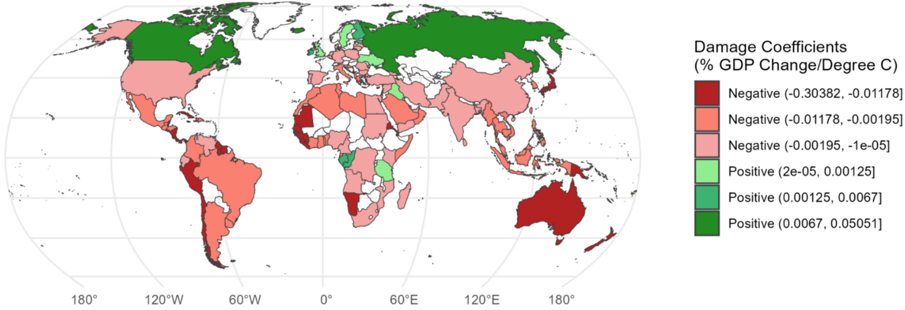



Example: Mexico's fisheries profit trajectories under different warming scenarios.

**Data Source:** Free et al. (2020) bioeconomic projections for 60% of global fisheries

**Method:**

- Compare profits under warming scenarios (RCP 4.5, 6.0, 8.5) vs. low-warming baseline (RCP 2.6)
- Assume "Full Adaptation" scenario (conservative estimate)
- Express profit changes as % of GDP to isolate climate effects
- $\sigma \Delta Profits_{ct} = \lambda_c^{fisheries} T_t + \varepsilon_{ct}$




Climate change impacts on fisheries profits as a percentage of GDP per degree of warming.

# Fisheries

## Non-Market Use Damage Function

Fisheries and mariculture are important sources of nutrients (Cheung et al. (2024))

1. Nutrient Projections (Cheung et al.)
   - Climate change → reduced availability of Ca, Fe, Omega-3, protein from seafood
   - Country-level projections linked to global temperature
2. Health Impact Assessment
   - Meta-analysis of epidemiological studies: nutrient intake → mortality risk
   - Account for country dependence on fisheries ($\mu_c$) and substitutability of nutrients (assumed 5%)
3. Economic Valuation
   - Monetize excess deaths using globally uniform VSL = \$7.4M
   - Scale VSL with global income growth over time
4. Plug into RICE50+

$$\textit{Health benefits}_{c,t} = (1 + \beta_c T_t) \cdot \textit{TAME} \cdot \textit{Pop}_{c,t} \cdot \mu_c \cdot \eta \cdot \textit{VSL}_t$$

# 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:

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

Back

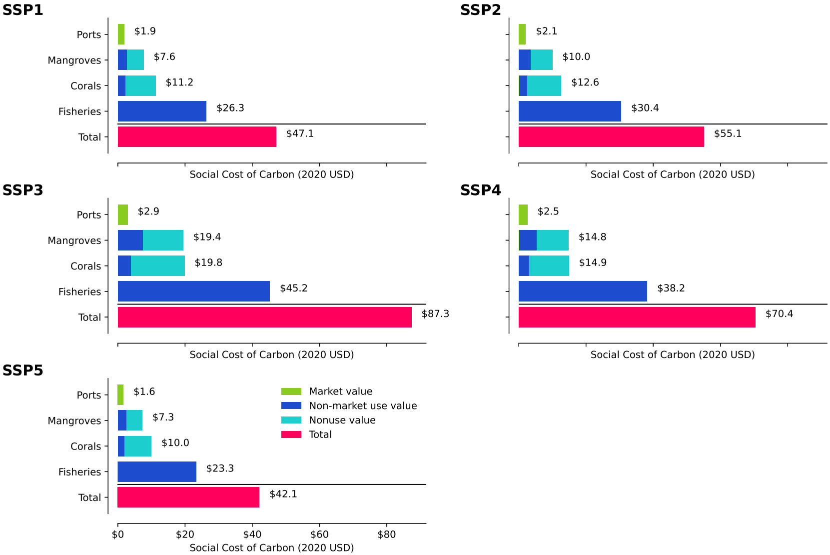
$$C_{c,t} = \widetilde{C}_{c,t} \cdot \left[ (1 + \lambda_{1,c}^{coral} + \lambda_{1,c}^{mangrove} + \lambda_{1,c}^{fish} + \lambda_{1,c}^{port}) \cdot \Delta T_t + (1 + \lambda_{2,c}^{mangrove}) \cdot \Delta T_t^2 \right]$$

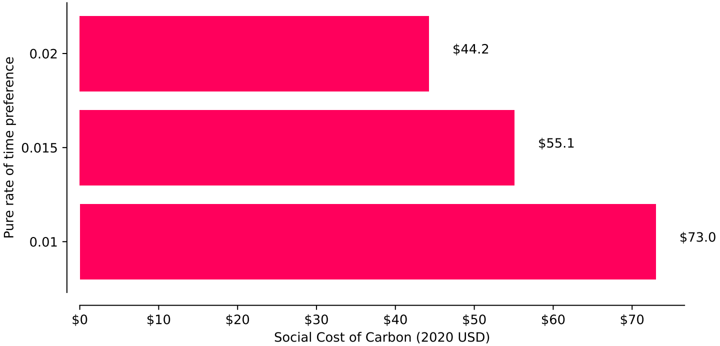
where $\widetilde{C}_{c,t}$ is consumption absent climate change damages to the ocean ecosystems.

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

Where

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


SSP1
Ports
Mangroves
Corals
Fisheries
Total
$1.9
$7.6
$11.2
$26.3
$47.1
Social Cost of Carbon (2020 USD)
SSP2
$2.1
$10.0
$12.6
$30.4
$55.1
Social Cost of Carbon (2020 USD)
SSP3
Ports
Mangroves
Corals
Fisheries
Total
$2.9
$19.4
$19.8
$45.2
$87.3
Social Cost of Carbon (2020 USD)
SSP4
$2.5
$14.8
$14.9
$38.2
$70.4
Social Cost of Carbon (2020 USD)
SSP5
Ports
Mangroves
Corals
Fisheries
Total
$1.6
$7.3
$10.0
$23.3
$42.1
Market value
Non-market use value
Nonuse value
Total
$0
$20
$40
$60
$80
Social Cost of Carbon (2020 USD)


0.02
0.015
0.01
Pure rate of time preference
$44.2
$55.1
$73.0
$0
$10
$20
$30
$40
$50
$60
$70
Social Cost of Carbon (2020 USD)

# Global sensitivity analysis - PAWN index

## PAWN index (Pianosi and Wagener, 2015)

- Moment-independent global sensitivity analysis method that measures input parameter influence on model output
- Compares unconditional output CDF with conditional CDFs (inputs fixed at different values) using Kolmogorov-Smirnov distance
  - Handles skewed, multimodal, or heavy-tailed distributions
  - No assumptions about linearity or normality
  - Robust with correlated inputs
  - Computationally efficient

Back

Brander, L., De Groot, R., Schägner, J., Guisado-Goñi, V., Van't Hoff, V., Solomonides, S., McVittie, A., Eppink, F., Sposato, M., Do, L., et al. (2024). Economic values for ecosystem services: A global synthesis and way forward. *Ecosystem Services*, 66:101606.

Cheung, W. W., Maire, E., Oyinlola, M. A., Robinson, J. P., Graham, N. A., Lam, V. W., MacNeil, M. A., and Hicks, C. C. (2023). Climate change exacerbates nutrient disparities from seafood. *Nature Climate Change*, 13(11):1242–1249.

Drupp, M. A., HÃďnsel, M. C., Fenichel, E. P., Freeman, M., Gollier, C., Groom, B., Heal, G. M., Howard, P. H., Millner, A., Moore, F. C., Nesje, F., Quaas, M. F., Smulders, S., Sterner, T., Traeger, C., and Venmans, F. (2024). Accounting for the increasing benefits from scarce ecosystems. *Science*, 383(6687):1062–1064.

Free, C. M., Mangin, T., Molinos, J. G., Ojea, E., Burden, M., Costello, C., and Gaines, S. D. (2020). Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PloS one*, 15(3):e0224347.

Sully, S., Hodgson, G., and van Woesik, R. (2022). Present and future bright and dark spots for coral reefs through climate change. *Global change biology*, 28(15):4509–4522.