The Green New Deal Dilemma

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Outline

The Green New Deal Dilemma

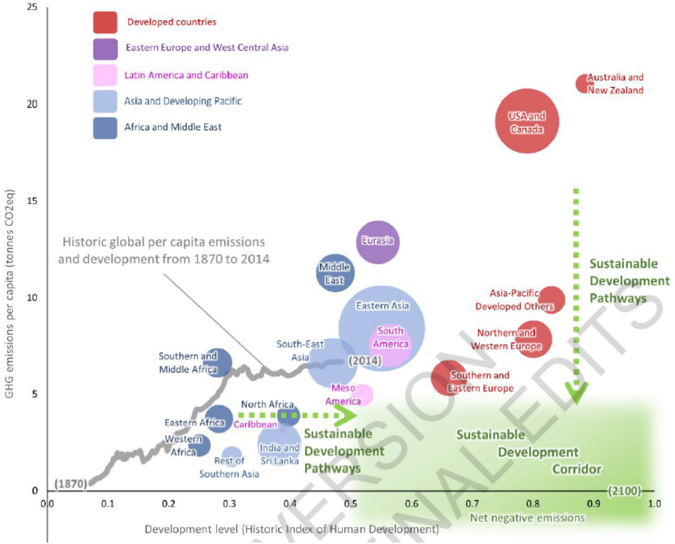
- Social priorities and environment priorities compete
- The benefits of preserving the environment will benefit future generations
- But social needs are urgent now, future generations will be more affluent
- Hence the imperative of taking account of inequalities in environmental policy

Outline

Take away

- Sustainability cannot be assessed without building scenarios of the future, measures based on current statistics may be misleading
- Sustainability approaches should not eliminate our quest for progress
- One should not mix the assessment of sustainability with the assessment of current well-being

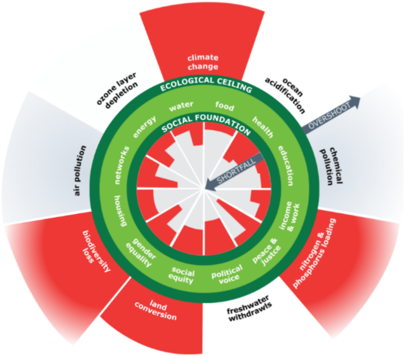
IPCC AR6 WG3 Technical Summary



The doughnut

Between planetary boundaries and social needs

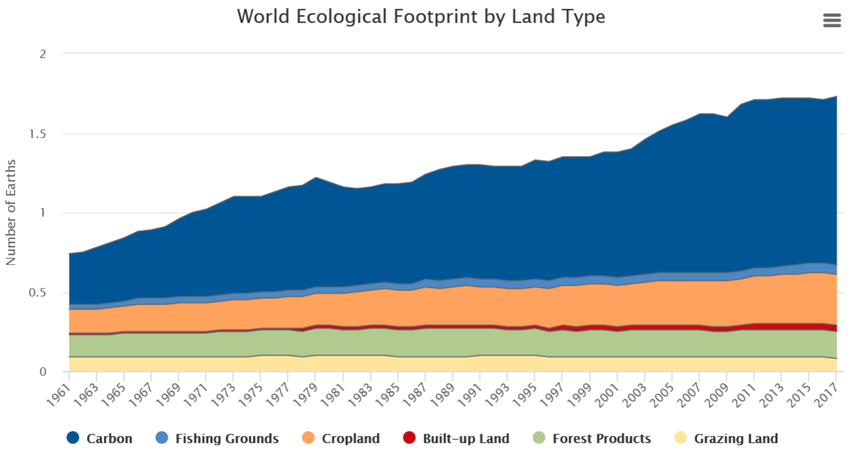
The Doughnut of social and planetary boundaries (2017)



Approach initiated by Kate Raworth (2017). See an excellent critical review by E. Schokkaert https://www.ejpe.org/journal/article/view/412/289

Ecological footprint

Surface needed to produce current production at current productivity, plus CO2 forest sink



Sustain what?

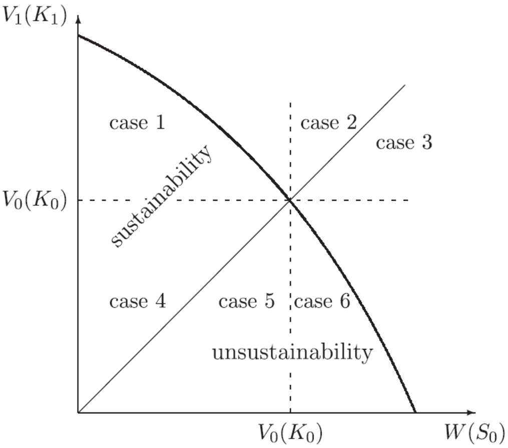
- Eco-system (strong sustainability): not plausible as ultimate value / too late
- Needs satisfaction (Brundtland Report, "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs"): too modest
- Welfare level (most of sustainability literature): still too modest?
- Growth (Llavador et al. 2011): utopian?
  - Makes sense for finite horizon
  - Decoupling and recycling makes it possible (energy supply is enormous)
  - Inequality reduction can raise social welfare by up to 20x

Basic theory

Pezzey 2004, Fleurbaey 2015

- Sequence of collective well-being $W_0, W_1, \dots$
- Every generation t makes decisions described by a vector S_t
- Set $P(S_0)$ of possible paths $(W_0, W_1, \dots)$
- A path $(W_0, W_1, \dots)$ sustains the level W_0 until T if for all $t = 1, \dots, T$, $W_t \geq W_0$ (adaptation to growth easy)
- Present actions S_0 are sustainable with respect to level W_0 until T if there is a path in $P(S_0)$ which sustains the level W_0 until T.
- Criterion: $W_0 \leq V_1$, where $V_1 = \max_{(W_0, W_1, \dots) \in P(S_0)} \min\{W_0, W_1, \dots\}$

A taxonomy of situations



Sustainability configurations.

Case 1: $W_0 < V_0 < V_1$	sustainable
Case 2: $V_0 < W_0 < V_1$	impossible
Case 3: $V_0 < V_1 < W_0$	impossible
Case 4: $W_0 < V_1 < V_0$	sustainable
Case 5: $V_1 < W_0 < V_0$	unsustainable
Case 6: $V_1 < V_0 < W_0$	unsustainable

Basic doubts

- "Ability" of future generations: what does that include? Political feasibility?
- Collective responsibility of future generations?
- Under uncertainty, does probable feasibility include innovation and learning?
- So: One should check intergenerational equity in a broader sense

Intergenerational social welfare

- Take $F(W_0, W_1, \ldots)$ such that $F(w, \ldots, w) = w$ (equally-distributed equivalent)
- Decomposition:

$$F(W_0, \ldots, W_T) = W_0 + \underbrace{F(W_0, V_1, \ldots, V_1) - W_0}_{\text{sustain-ability}}$$

$$+\underbrace{F(W_0, \ldots, W_T) - F(W_0, V_1, \ldots, V_1)}_{\text{sustain-actuality}}$$

- This can be adapted to expected values under uncertainty
- The worrisome case is when sustainability is achieved but not sustainactuality

An alternative approach

Arrow et al. (2010), Dasgupta and Mäler (2000)

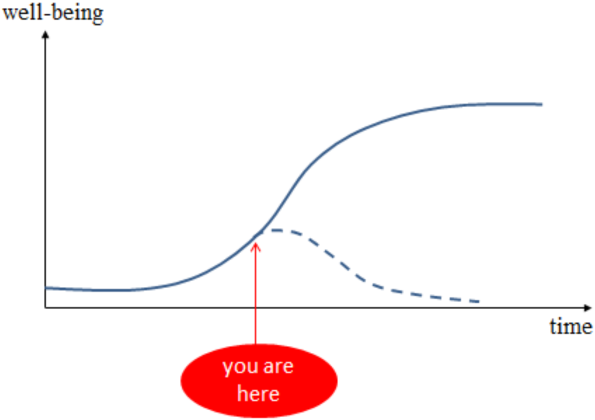
- The present generation's actions S_0 are sustainable if

$$F(W_0, W_1, ...) \leq F(W_1, W_2, ...)$$

- This makes sense only with a stationary criterion and an infinite horizon
- It requires determining how $F(W_1, W_2, ...)$ depends on S_0 (the first approach needs a prediction of the future realization only for sustainactuality, not for sustainability)
- Compatible with sure decline in W_t in the future (Asheim 2007)

Deeper doubts

- Should we really sustain anything (level or growth)?
- Suppose the best path for life on Earth is a transition to an era of greater well-being: sustaining growth is asking for too much, sustaining level for too little



Genuine savings

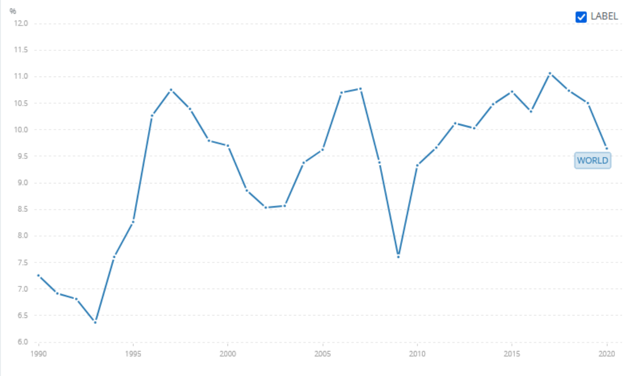
- Basic idea: write $V_1(S_0)$
- Compare $V_1(S_0)$ to $V_0(S_{-1})$: is there a link with sustainability ($W_0 \leq V_1(S_0)$)?
- It is not possible to have $V_0(S_{-1}) < W_0, V_1(S_0)$
- Therefore: $V_0(S_{-1}) < V_1(S_0)$ implies $W_0 \leq V_0(S_{-1})$, hence $W_0 \leq V_1(S_0)$
- $V_1 - V_0 > 0$ is a sufficient, not a necessary condition for sustainability ($V_1 - V_0 \geq 0$ is not sufficient)

Accounting prices

- But achieving sustainability with $V_1 - V_0 < 0$ looks bad (destroying the future while spoiling the present)
- So, $V_1 - V_0 > 0$ is a reasonable condition
- Accounting prices for components of S_0 are derived from

$$\sum_k \frac{\partial V_1}{\partial S_{0k}} (S_{0k} - S_{-1k}) > 0$$

Inclusive wealth
Adjusted net savings (world) - World Bank



net national savings plus education expenditure and minus energy depletion, mineral depletion, net forest depletion, and carbon dioxide and particulate emissions damage

Can one avoid predicting the future?

- If S_0 is a single capital good (and no technical progress), checking $S_0 < S_1$ is enough
- Multiple goods and technical progress complicate the picture considerably
- Question: What do we gain by computing $\sum_k \frac{\partial V_1}{\partial S_{0k}} \left(S_{0k} - S_{-1k}\right)$ rather than V_1 directly?
- It is actually harder: counterfactual scenarios around values of S_0 are needed, in order to compute derivatives
- In contrast, computing $V_1\left(S_0\right)$ involves only looking at actual value of S_0
- Looking for scenarios? Check the Shared Socioeconomic Pathways (Rao et al. 2019, Riahi et al. 2017)

Ecological footprint revisited

- A relevant ecological footprint can be found by solving this equation for λ
$$W_0 = V_1\left(\lambda K_0^n, K_0^h\right)$$
where $S_0 = \left(K_0^n, K_0^h\right)$ depicts natural and human-made capital
- $\lambda \leq 1$ if and only if $W_0 \leq V_1$
- Like genuine savings, this involves computing counterfactuals, and far away from S_0
- But errors in the estimate may not matter much

Greening income statistics?

- Green GDP=GDP - capital depreciation
- Comparing consumption to green GDP is another way to check sustainability
- But green GDP itself is not a relevant index: it depicts neither the current situation nor the future prospects
- One should keep two questions separate: 1) How well off is the present generation? 2) How well does it prepare for the future?
- Weitzman 1976: green GDP ("net national product") may represent intergenerational social welfare (more precisely, the equivalent level of constant consumption)

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Outline

Take away

- Discounting is not dirty, it is a necessity because a $ has different value depending on the social priority of different people at different times
- There is a simple formula to understand the value of the "social discount rate"
- In the long-run, only the poorest (present and future) stakeholders of contemplated programs matter for the evaluation

Discounting

- Discounting is a central tool in intertemporal economic analysis.
- The difficulty is that we have to compare current costs/benefits with future (long-run and uncertain) costs/benefits.
- The question of how to price the future is of course crucial for energy policy, and policies dealing with the climate change issue.
- Example: the social cost of carbon.

Discounting and net present value

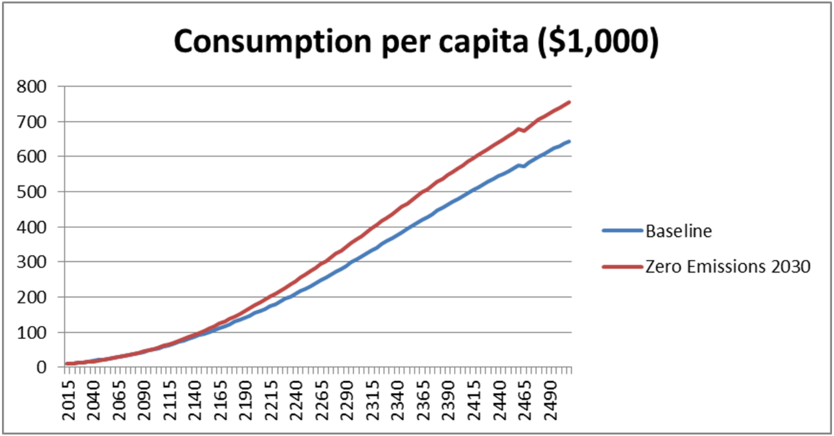
- A key tool of evaluate policies/projects is to compute their Present Value (PV).
- If the policy/project P generates (net) flows F_t , its NPV is:

$$NPV(P) = \sum_{t=0}^{T} e^{-\rho_t t} F_t$$

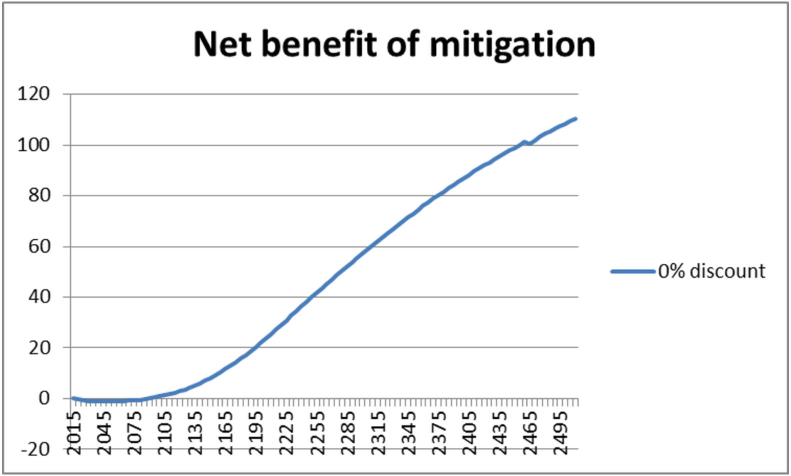
  where ρ_t is the discount rate: we put less weight on future costs/benefits.
- Another formula is $\sum_{t=0}^{T} \left(\frac{1}{1+\rho_t}\right)^t F_t$
- If the NPV is positive, the project/policy improves on the status quo (but may not be the best).

Illustration

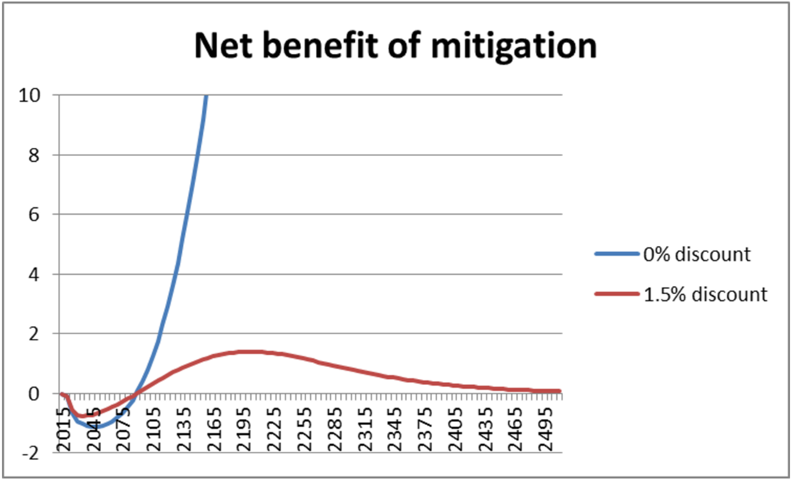
BAU vs. decarbonizing in 2030 (from DICE2016)



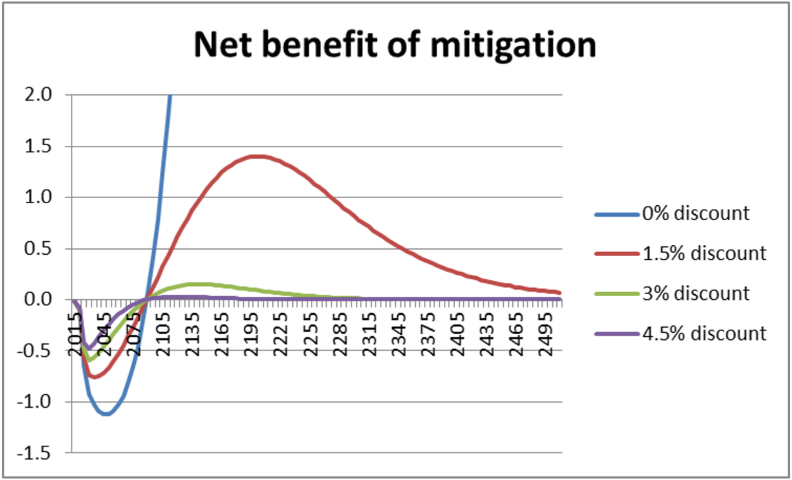
Net costs and benefits (no discounting)



With mild discounting



With more standard discounting



Discount rate and minimal return

- Consider a project costing c_0 and yielding $c_0 e^{Rt}$ (rate of return R per year: $e^{Rt} \simeq (1+R)^t$):

$$NPV = -c_0 + c_0 e^{(R-\rho_t)t}$$

- This is positive if and only if

$$e^{(R-\rho_t)t} > 1 \Leftrightarrow R > \rho_t$$

The social cost of carbon

- The social cost of carbon (SCC) is just a particular application of the NPV concept.
- The SCC is the NPV of all future damages (D_t) related to the emission of an extra ton of CO2 in the atmosphere:

$$SCC_0 = \sum_{t=0}^{T} e^{-\rho_t t} D_t$$

- The SCC can also be computed for a future period—and is likely to increase

The SCC depends crucially on the discount rate

EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances (Sept. 2022)

Table 3.1.1: Social Cost of Carbon (SC-CO_2) by Damage Module, 2020-2080 (in 2020 dollars per metric ton of CO_2)

	Near-Term Ramsey Discount Rate and Damage Module								
	2.5%			2.0%			1.5%		
Emission Year	DSCIM	GIVE	Meta-Analysis	DSCIM	GIVE	Meta-Analysis	DSCIM	GIVE	Meta-Analysis
2020	110	120	120	190	190	200	330	310	370
2030	140	150	150	230	220	240	390	350	420
2040	170	170	170	280	250	270	440	390	460
2050	210	200	200	330	290	310	500	430	520
2060	250	220	230	370	310	350	550	470	570
2070	280	240	250	410	340	380	600	490	610
2080	320	260	280	450	360	410	640	510	650

Justifying discounting: the social discount rate (SDR)

- Consider a small change to a consumption path, from $C_t, t = 0, ..., T$ to $C_t + F_t, t = 0, ..., T$
- Is that a good change? Let us invoke a SWF $W\left(U_t\left(C_t\right), t = 0, ..., T\right)$

$$dW \simeq \sum_{t=0}^{T} \frac{\partial W}{\partial U_t} \frac{\partial U_t}{\partial C_t} F_t = \sum_{t=0}^{T} \beta_t F_t$$

  where β_t is the marginal social value of money for “generation” t
- Let us write it in terms of current consumption ($):

$$\frac{dW}{\beta_0} = \sum_{t=0}^{T} e^{-\ln \frac{\beta_0}{\beta_t}} F_t$$

  justifying $\rho_t = \frac{1}{t} \ln \frac{\beta_0}{\beta_t}$

Interpreting the result

- $\ln \frac{\beta_0}{\beta_t}$ is the relative priority (in percentage) of C_0 over C_t
- Why should C_0 have any priority over C_t?
  - pure time preference
  - uncertainty about the future
  - the future is expected to be richer

The Ramsey formula

- Consider the CRRA function $U(C) = \frac{C^{1-\eta}}{1-\eta}$ and the discounted utilitarian function $W = \sum_{t=0}^{T} e^{-\delta t} U(C_t)$
- Then

$$\beta_t = e^{-\delta t} C_t^{-\eta}$$

$$\ln \frac{\beta_0}{\beta_t} = -\eta \ln C_0 + \delta t + \eta \ln C_t$$

$$\boxed{\text{Ramsey formula: } \rho_t = \delta + \eta \frac{1}{t} \ln \frac{C_t}{C_0}}$$

- δ may capture pure time preference, as well as the risk of extinction ($e^{-\delta t} \simeq (1-\delta)^t$: probability of still existing in t if the extinction risk at each period is δ)
- $\frac{1}{t} \ln \frac{C_t}{C_0}$ is the average growth rate per year between 0 and t

Why pure time preference is popular

- In an infinite horizon model, the sum $\sum_{t=0}^{\infty} U(C_t)$ is generally not defined
- Exception (Ramsey): U tends to zero from below as $C_t \to +\infty$ (zero is the "bliss" utility)
- Koopmans (1960) offered axiomatization of discounted utilitarianism $\sum_{t=0}^{\infty} e^{-\delta t} U(C_t)$ (assuming bounded U—if U grows at rate greater than δ, this sum is again not defined)

A fundamental problem with infinite horizon

- Anonymity and Strong Pareto are incompatible

$$\mathbf{x} = (1, 0, 1, 0, 1, 0, \cdots)$$

$$\mathbf{x}' = (1, 1, 0, 1, 0, 1, \cdots)$$

$$\mathbf{x}'' = (1, 1, 1, 0, 1, 0, \cdots)$$

- Anonymity and Weak Pareto are also incompatible

$$\mathbf{x} = \left(\frac{1}{3}, \frac{2}{3}, \frac{1}{4}, \frac{3}{4}, \frac{1}{5}, \frac{4}{5}, \cdots\right)$$

$$\mathbf{x}' = \left(\frac{1}{4}, \frac{1}{3}, \frac{1}{5}, \frac{2}{3}, \frac{1}{6}, \frac{3}{4}, \cdots\right)$$

- Even finite anonymity and Weak Pareto are only weakly compatible: social preferences exist but are not constructible

How to deal with it?

1. Consider a finite horizon and a finite population
2. Take finite anonymity and accept incompleteness:
   1. overtaking (strict preference): there is T_0 such that for all $T > T_0$, greater $\sum_{t=0}^{T} U(C_t)$
   2. catching-up (weak preference): for all $\varepsilon > 0$, there is T_0 such that for all $T > T_0$, $\sum_{t=0}^{T} U(C_t)$ is greater by at least $-\varepsilon$
3. Weaken Pareto and possibly accept incompleteness:
   1. greater $\liminf_{T\to\infty} \sum_{t=0}^{T} U(C_t)$
   2. rank-discounted utilitarianism (Zuber & Asheim 2012): $\sum_{t=0}^{\infty} e^{-\delta t} U\left(C_{[t]}\right)$, where $\left(C_{[t]}\right)$ is re-ordered in increasing fashion (incomplete as not all streams can be reordered in this way; it satisfies Strong Pareto on the streams that can)

Introducing risk

- States of the world s
- Expected social welfare

$$dEW \simeq \sum_{t=0}^{T} \sum_{s} p_s \frac{\partial W_s}{\partial U_{st}} \frac{\partial U_{st}}{\partial C_{st}} F_{st} = \sum_{t=0}^{T} \sum_{s} p_s \beta_{st} F_{st}$$

- One has $\sum_s p_s \beta_{st} F_{st} = \left(\sum_s p_s \beta_{st}\right) \left(\sum_s p_s F_{st}\right) + \text{Cov}\left(\beta_t, F_t\right) = E\beta_t EF_t + \text{Cov}\left(\beta_t, F_t\right)$
- The term $\text{Cov}\left(\beta_t, F_t\right)$ is positive if benefits fall in high priority states (insurance-type project)

The "beta" of the project

- One computes ρ_t by solving

$$e^{-\rho_t t} EF_t = \sum_s p_s \frac{\beta_{st}}{\beta_0} F_{st} = \frac{E\beta_t EF_t + \mathrm{Cov}\left(\beta_t, F_t\right)}{\beta_0}$$

- This implies

$$e^{-\rho_t t} = \frac{E\beta_t EF_t + \mathrm{Cov}\left(\beta_t, F_t\right)}{\beta_0 EF_t} = \frac{E\beta_t}{\beta_0}\left(1 + \frac{\mathrm{Cov}\left(\beta_t, F_t\right)}{E\beta_t EF_t}\right)$$

$$\rho_t = -\frac{1}{t}\left(\ln\frac{E\beta_t}{\beta_0} + \ln\left(1 + \frac{\mathrm{Cov}\left(\beta_t, F_t\right)}{E\beta_t EF_t}\right)\right)$$

$$\simeq -\frac{1}{t}\ln\frac{E\beta_t}{\beta_0} - \frac{1}{t}\frac{\mathrm{Cov}\left(\beta_t, F_t\right)}{E\beta_t EF_t}$$

Introducing inequality and risk

Fleurbaey & Zuber (2013, 2015)

- One can compute a specific discount rate for a transfer from one person i in 0 to another person j in t and in a particular state of the world

$$\rho_{ijts} = \frac{1}{t} \ln \frac{\beta_{i0}}{\beta_{jts}}$$

- When evaluating a policy with many stakeholders, the SDR over the volume of investment is an average of such person-to-person-state rates, weighted by their relative shares in the costs/benefits

$$\rho_t = \frac{1}{t} \ln \frac{\sum_i \beta_{i0}\sigma_{i0}}{\sum_s p_s \sum_j \beta_{jts}\sigma_{jts}} = \frac{1}{t} \ln \sum_i \frac{1}{\sum_s p_s \sum_j \frac{\beta_{jts}\sigma_{jts}}{\beta_{i0}\sigma_{i0}}}$$

$$= \frac{1}{t} \ln \sum_i \frac{1}{\sum_s p_s \sum_j \frac{\sigma_{jts}}{\sigma_{i0}} e^{-\rho_{ijts} t}}$$

Long-run SDR under inequality and risk

- Formula
$$\rho_t = \frac{1}{t} \ln \sum_i \frac{1}{\sum_s p_s \sum_j \frac{\sigma_{jts}}{\sigma_{i0}} e^{-\rho_{ijts} t}}$$
When $t \to \infty$, the expected value $\sum_s p_s \sum_j \frac{\sigma_{jts}}{\sigma_{i0}} e^{-\rho_{ijts} t}$ is dominated by $\min_{j,s} \rho_{ijts}$, i.e., by $\max_{j,s} \beta_{jts}/\beta_{i0}$: the worst-case scenario for the worst-off in the future
- And the term $\sum_i e^{\min_{j,s} \rho_{ijts} t}$ is dominated by $\max_i \min_{j,s} \rho_{ijts}$, i.e., by $\max_i \min_{j,s} \beta_{i0}/\beta_{jts}$: the worst-off in the present
- Simple lesson: in the long run, the SDR only depends on the worst: poorest people now and in the future, in the worst state of the world
- The shares and probabilities do not matter—they only affect the speed of convergence to the long-run SDR

The discounting debate

Positive/descriptive vs. normative/prescriptive (Arrow et al. 1995, Posner and Weisbach 2007, Stern 2014)

- Normative: rely on a SWF
- Positive: rely on market interest rates—which ones: Treasury bonds or NASDAQ?
- Arguments of the positive school:
  - opportunity cost: the market interest rate is the normal rate of return of investments, and using another threshold to select investments will lead either to rejecting good projects (if the SDR is too high) or accepting bad projects (if low SDR, one should rather invest on the market)
  - market rates reflect the population preferences

The opportunity cost argument is wrong

- If the growth path is socially optimal,

$$\frac{\beta_0}{\beta_t} = e^{Rt}$$

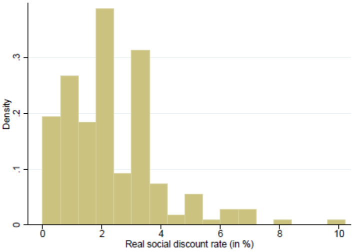
  and the two methods coincide
- If the growth path is not optimal, the market may reject socially good projects (R is too high, under-accumulation) or accept socially bad projects (R is too low, over-accumulation)
- Whatever the SDR, a project that dominates another (better flow at all periods) is never rejected. So the argument that, if the SDR is too low, it will accept projects dominated by investments at the market rate is logically invalid: confusion between acceptable project and best project

The democratic argument is dubious

- The market rate is likely to reflect intra-generational preferences
- For long-term policies, one needs social inter-generational preferences: the market rate is unlikely to be aligned with reasonable inter-generational preferences
- The market rate is fine and "democratic" if the growth path is socially optimal and reflects inter-generational altruism
  - if the growth path is not socially optimal or the market rate does not reflect inter-generational altruism, then one needs to assess the gap between the chosen SWF and altruism
  - key reason why the market rate is unlikely to reflect inter-generational altruism: collective action problem. People may want to save the Planet through their investment, but cannot do so alone, and thus only invest in their family wealth

Survey among experts

Drupp et al. (2018)



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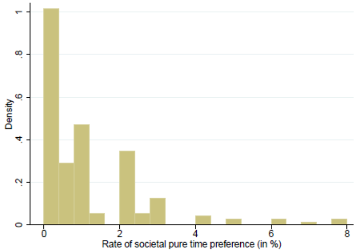

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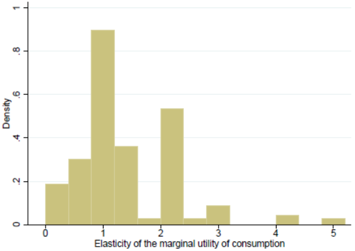

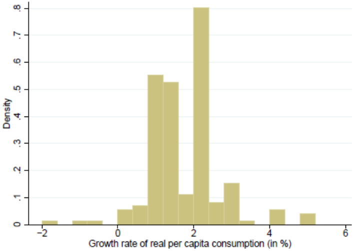

Compare with...

- IPCC (AR5, WG3): “a relative consensus emerges in favour of $\delta = 0$ and η between 1 and 3, although they are prescriptive parameters."

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Outline

Take away

- Integrated assessment models provide scenarios and carbon pricing insights
- Inequality between generations should not hide inequalities within generations, which are relevant (recall discounting in the presence of inequalities)
- Co-benefits in air pollution and social redistribution alter carbon abatement recommendations
- Population scenarios and national social policies may interfere with global carbon policy

Integrated assessment models

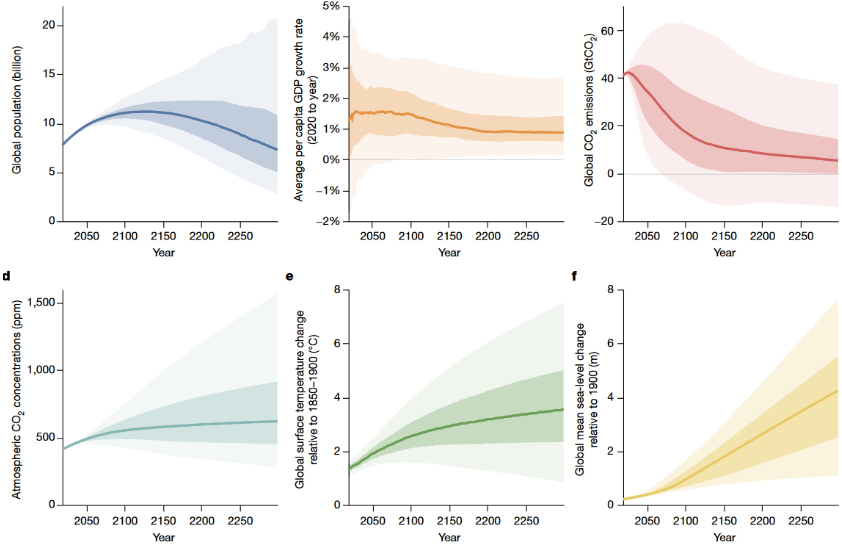
- Integrated Assessment Models (IAMs) are numerical models of the climate and the economy used to study the interactions between the two systems.
- Such models have been important to shape climate policy: in the US, regulatory rules regarding the Social Cost of Carbon are based on such models.

Different types of models

- Cost-benefit analysis IAMs (CBA IAMs): few sectors, simplied models, used for optimization and cost-benet analysis.
  - Numerical models: PAGE (Hope et al., 1993); DICE (Nordhaus, 1994); RICE, (Nordhaus and Yang, 1996); FUND (Tol, 1997); NICE (Budolfson et al., 2015); GIVE (Rennert et al. 2022)
  - Models with closed form solutions: Golosov, Hassler, Krusell, Tsyvinski (2014); Traeger (2021).
- Detailed-process IAMs (DP-IAMs) used to perform cost-eectiveness analysis given a trajectory xed in climate agreements (e.g.: Re-MiND; WITCH, IMACLIM).

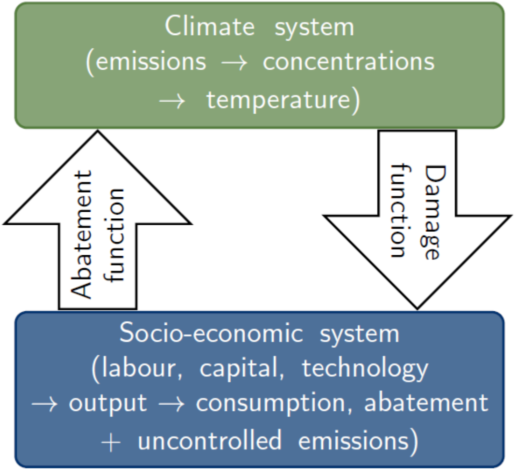
Long-term scenarios

Example (Rennert et al. 2022, GIVE model)



Structure of a CBA IAM

Stanton et al. (2009)



How is policy designed with such a model?

- With CBA-IAMs:
  - One technique takes a reference scenario and computes the SCC alongside the scenario—this is supposed to be indicative of the recommended carbon price (implemented through a tax or a cap-and-trade mechanism)
    - Beware: unless the path is optimal with respect to the social welfare function (SWF) used to compute the SCC, the optimal carbon tax differs from the SCC
  - Model the abatement of GHG as a function of the carbon price, and compute the optimal carbon price over time in the model, maximizing the SWF
- With bottom-up models: cost-effectiveness analysis, for a given carbon budget or decarbonization path (i.e., how to distribute abatement effort across sectors and industries)

Why does the SCC rise with time

- Hotelling rule for a depleted resource (arbitrage): its price should increase at the market interest rate—this assumes optimal accumulation path
- More direct reasons for the SCC to rise (no optimality assumed):

$$SCC_{T_0} = \sum_{t=T_0}^{T} e^{-\rho_t(t-T_0)} D_t$$

  - The damage curve is convex: the later tons emitted generate more damage as they arrive in a warmer world. Thus the marginal damages D_t rise over time
  - If there is uncertainty, ρ_t decreases in t, hence $e^{-\rho_t(t-T_0)}$ goes up (with T_0, for any given $t - T_0$)

Can we learn anything from IAMs?

- Some people argue that we cannot learn anything from IAMs because of the inherent underlying uncertainties in the models. Even worse, IAMs may create a false sense of knowledge and precision (Pindyck, 2013).
- One of the key element of Pindyck's line of argument: we do not know the "correct value" of the social discount rate.
- But he misses the point that this is a normative debate.
- We should certainly be very cautious with the specic numbers obtained by IAMs, in particular the social cost of carbon. However, IAMs may be useful to identify key issues to build a more informed public discussion.

Dealing with inequality

- CBA-IAMs optimize using a discounted utilitarian social welfare function—thus, they typically focused on intergenerational inequality
- Climate impacts are likely to disproportionately hurt the future poor (World Bank 2016; Hsiang et al. 2017).
- Social cost of carbon literature took inequalities into account using equity weights: Azar and Sterner (1996); Fankhauser et al. (1997); Pearce (2003); Anthoff et al. (2009).
- A specic issue: IAMs (in particular RICE) used to include Negishi weights, i.e. weights on the welfare of the different regions to bracket out inequality from climate policy design
- Until recently: no inequalities within (big) regions. And not much work on the differentiated impacts of climate change.

Unequal impacts vs. the discounting debate

Dennig et al. (2015)

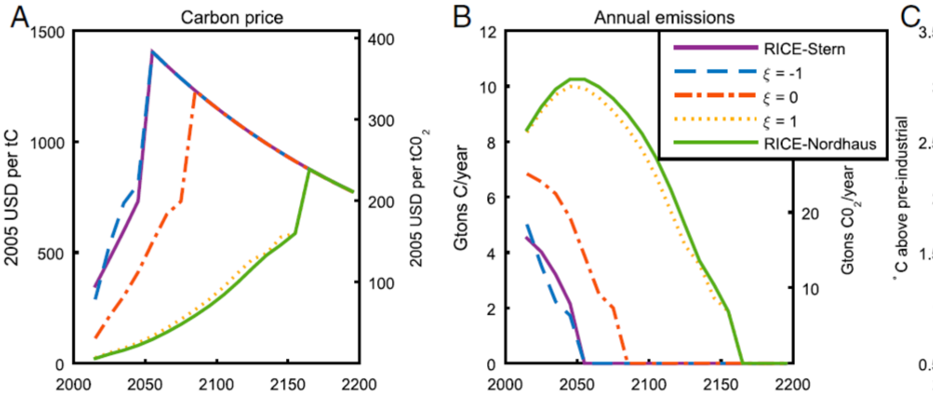
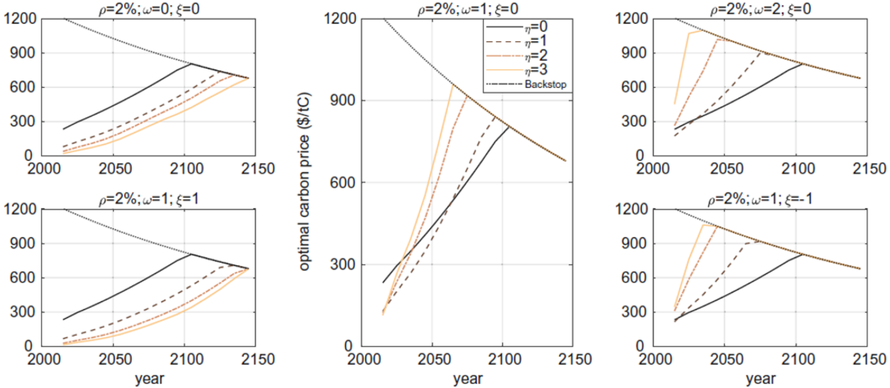


Fig. 1. The three panels plot model outcomes in NICE for different values of the income elasticity of damage: $\xi =$
policies in our implementation of RICE for the (different) specific assumptions about discounting endorsed by Nordha
similar, as are RICE-Stern and $\xi = -1$. (*A*) Optimal policy (carbon price trajectories). The descending line eventually join
trajectory of the maximum of the regional backstop prices. (*B*) The total emission rates for these policies. (*C*) The co

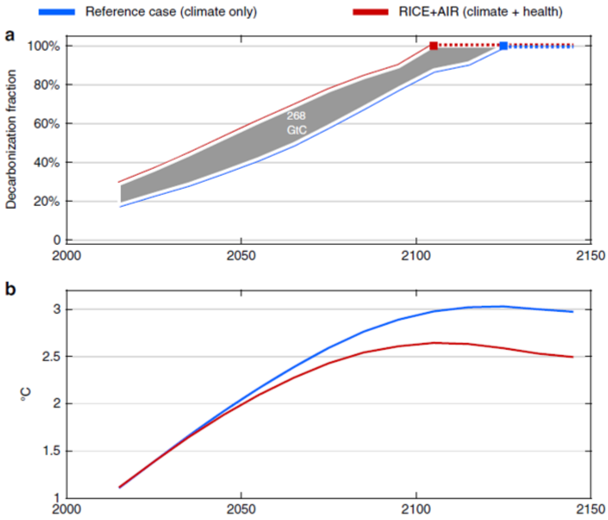
Can inequality aversion push mitigation?

Budolfson et al. (2017)



Air pollution and health co-benefits

Scovronick et al. (2019)



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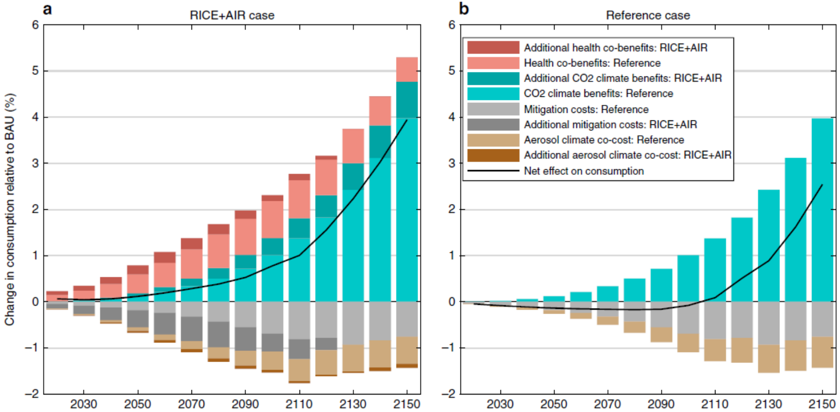
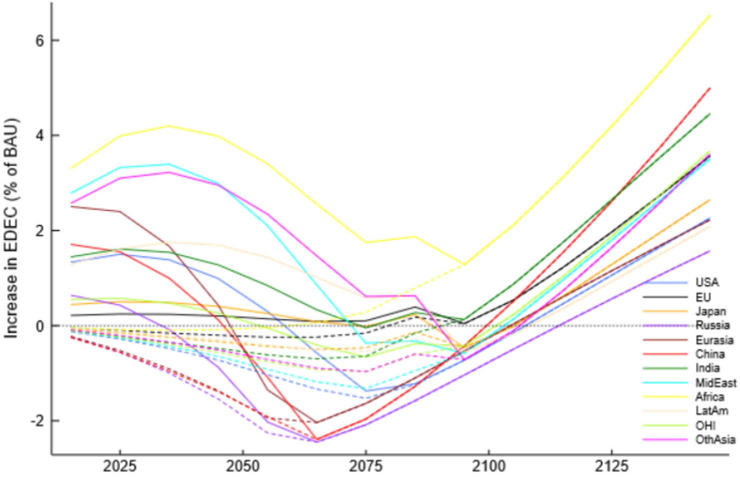


a
RICE+AIR case
b
Reference case
Change in consumption relative to BAU (%)
6
5
4
3
2
1
0
−1
−2
2030
2050
2070
2090
2110
2130
2150
Additional health co-benefits: RICE+AIR
Health co-benefits: Reference
Additional CO2 climate benefits: RICE+AIR
CO2 climate benefits: Reference
Mitigation costs: Reference
Additional mitigation costs: RICE+AIR
Aerosol climate co-cost: Reference
Additional aerosol climate co-cost: RICE+AIR
Net effect on consumption

Tax recycling (uniform lump-sum)
Budolfson et al. (2021)



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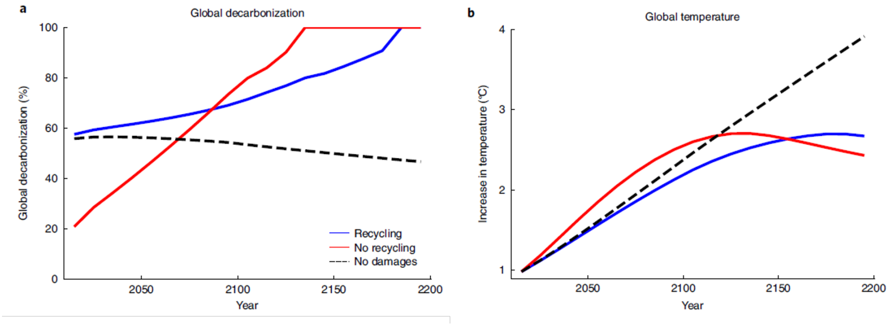
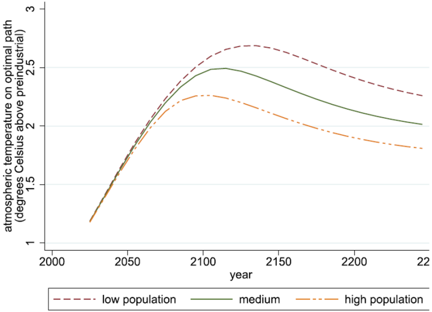
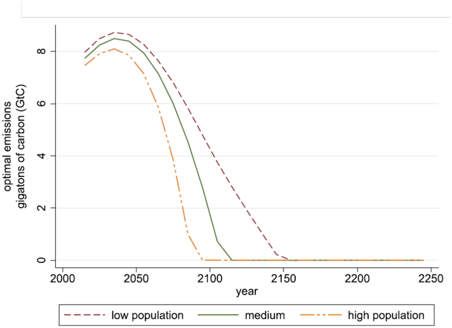

a
Global decarbonization
Global decarbonization (%)
100
80
60
40
20
0
2050
2100
2150
2200
Year
Recycling
No recycling
No damages
b
Global temperature
Increase in temperature (°C)
4
3
2
1
2050
2100
2150
2200
Year

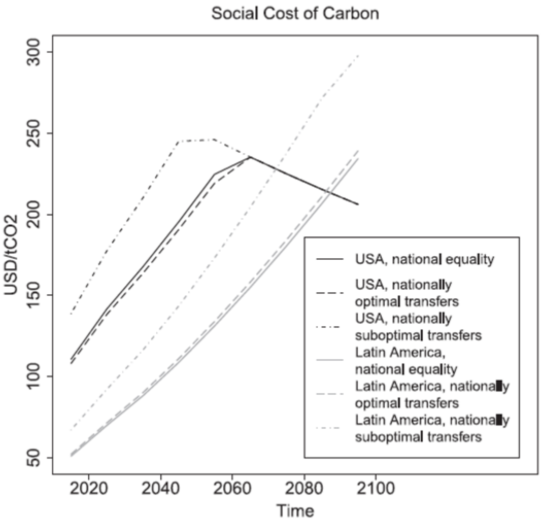
Population scenarios

Budolfson et al. (2019)





Suboptimal national distributions
Kornek et al. (2021)



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