Pigou's Advice and Sisyphus' Warning: Carbon Pricing with Non-Permanent Carbon-Dioxide Removal

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with
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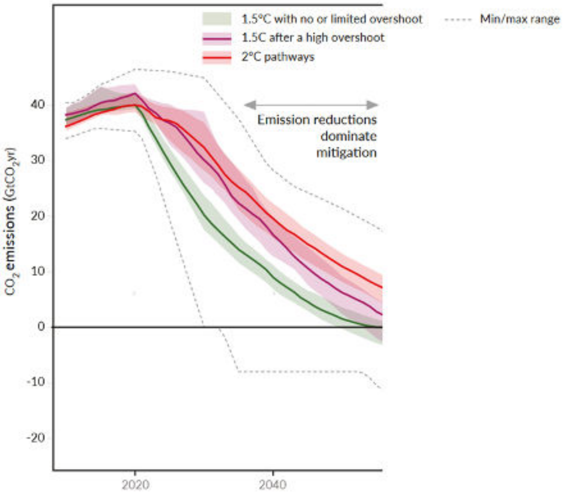
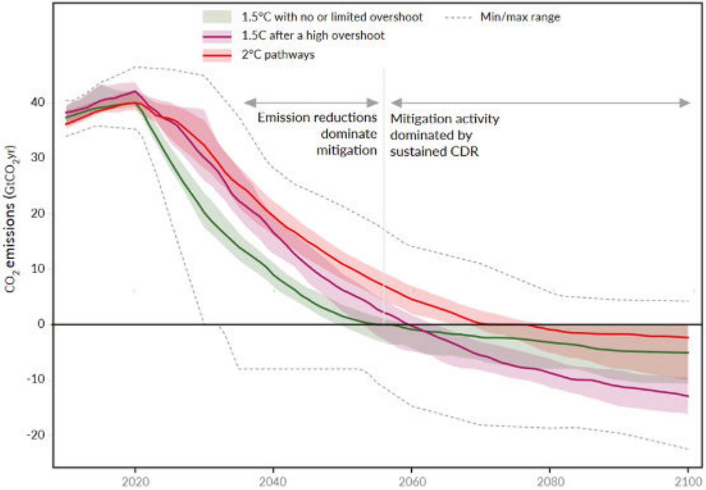
Why we need to talk about carbon removal



State of CDR (2023)

Why we need to talk about carbon removal



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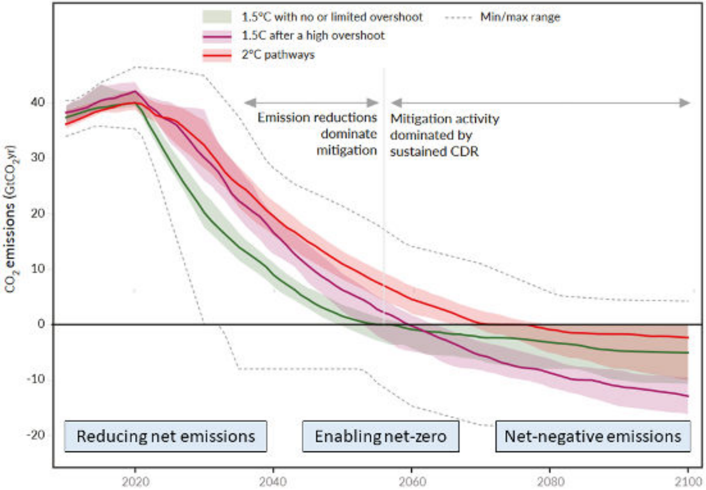

State of CDR (2023)

Diverse range of removal and storage technologies. . .

Direct Air Capture

Afforestation

. . . with substantially different duration of storage

Direct Air Capture

> 10,000 years

Afforestation

decades to centuries

CDR-Options Differ in Permanence of Storage

Removal and storage pathway	Storage duration *(half-life)*
Bioenergy with carbon capture and storage	millennia
Enhanced weathering	centuries
Forestry techniques & wood products	decades to centuries
Single family home	*100*
Furniture, residential upkeep and improvement	*30*
Paper	*2*
Soil carbon sequestration techniques	years to decades
Biochar	centuries

Table: Storage time for different CO2 removal technologies.

Research questions and methods

Research questions

1. How to value non-permanent carbon dioxide removal?

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2. What's the role of *non-permanent* carbon removal for long-run climate mitigation?

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3. How to design policy instruments for non-permanent removal?

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Method

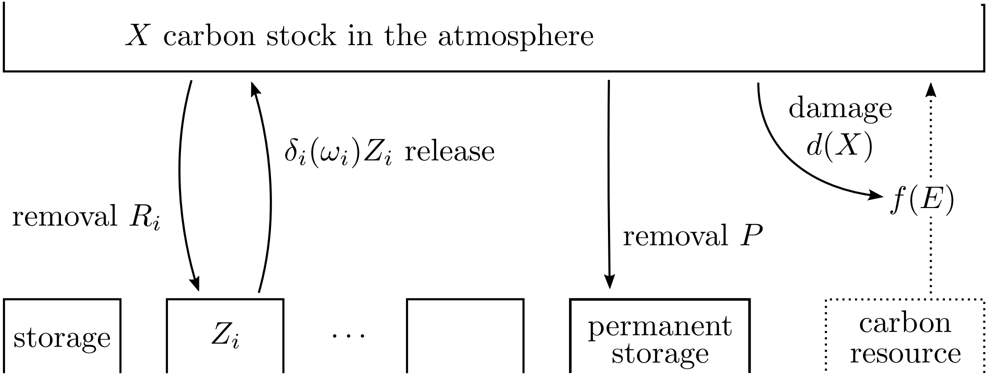
- Dynamic partial equilibrium model

Literature

- Vast **literature on costs and potentials** of technologies (Minx et al. 2018, Fuss et al. 2018, Nemet et al. 2018; Smith et al. 2023]
- Only **few economic studies** on carbon removal policies:
    - Carbon removal and interregional leakage (Franks et al. 2022)
    - Incentivising permanent removals (Lemoine, 2021)
    - Forest management and carbon sequestration in forests (Tahvonen 1995, Sedjo and Sohngen 2012)
    - Pricing for non-permanent carbon removal (Groom and Venmans 2022, Bednar et al. 2021, Kim et al. 2008, van Kooten 2009)
- **Our contribution:** analysis of non-permanent carbon removal in a **dynamic partial equilibrium model with endogenous carbon prices**

Model

Model – Overview



R_i is removed and stored in Z_i but a fraction $\delta_i Z_i$ is released

Model – Welfare Maximization

$$\max_{E,P,R_i,\delta_i} \int_0^{\infty} [\underbrace{\widetilde{f}(E,t)}_{\text{production}} - \underbrace{\widetilde{h}(P,t)}_{\substack{\text{permanent}\\ \text{removal costs}}} - \underbrace{\textstyle\sum_i \widetilde{g}_i(R_i,t)}_{\substack{\text{non-permanent}\\ \text{removal costs}}} - \underbrace{\textstyle\sum_i w_i(\delta_i)Z_i}_{\text{diligence cost}} - \underbrace{d(X)]}_{\text{climate damages}} \quad e^{-rt}dt$$

$$\begin{aligned} \text{s.t.} \quad & \dot{X} = E - P - \textstyle\sum_i R_i + \textstyle\sum_i \delta_i Z_i && \perp \mu && \text{atmospheric carbon stock} \\ & \dot{Z}_i = R_i - \delta_i Z_i && \perp \psi_i && \text{non-permanent storage stocks} \end{aligned}$$

First-Order Conditions

$$\text{Fossil energy use:} \quad f'(E)\Delta^{E}(t) = -\mu(t) \tag{1}$$

$$\text{Permanent removal:} \quad h'(P)\Delta^{P}(t) = -\mu(t) \tag{2}$$

$$\text{Non-permanent removal:} \quad g_i'(R_i)\Delta^{R_i}(t) = \psi_i(t) - \mu(t) \tag{3}$$

$$\text{Diligence:} \quad w_i'(\delta_i(t)) = -(\psi_i(t) - \mu(t)) \tag{4}$$

$$\dot{\mu}(t) = r\mu(t) + d'(X) \tag{5}$$

$$\dot{\psi}_i(t) = (r + \delta_i(t))\psi_i(t) - \delta_i(t)\mu(t) + w_i(\delta_i(t)) \tag{6}$$

$$0 = \lim_{t\to\infty} \mu(t)X(t)e^{-rt} \tag{7}$$

$$0 = \lim_{t\to\infty} \psi_i(t)Z_i(t)e^{-rt} \tag{8}$$

Agenda

Research questions

1. **How to value non-permanent carbon dioxide removal?**
2. What's the role of *non-permanent* carbon removal for long-run climate mitigation?
3. How to design policy instruments for non-permanent removal?

Interpretation of shadow prices

Shadow price on atmospheric carbon stock X (μ)

$$-\mu = \underbrace{\int_t^{\infty} d'\left(X(s)\right) e^{-r(s-t)} ds}_{\text{Social Cost of Carbon } (SCC_E)}$$

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Shadow price on non-permanent sink Z_i (ψ)

$$\begin{aligned}
-\psi_i &= \left[\int_t^\infty \delta_i(s) SCC_E(s) + w\left(\delta_i(s)\right)\right] e^{-\int_t^s (r+\delta(v))dv} ds \\
&= \underbrace{\int_t^\infty \delta_i(s) SCC_E(s) e^{-\int_t^s (r+\delta(v))dv} ds}_{\text{Social Cost of Carbon Removal } (SCC_R)} + \underbrace{\int_t^\infty w\left(\delta_i(s)\right) e^{-\int_t^s (r+\delta(v))dv} ds}_{\text{Intertemporal Diligence Cost (IDC)}}
\end{aligned}$$

Optimal deployment satisfies: $g'(R) = SCC_E - SCC_R - IDC$

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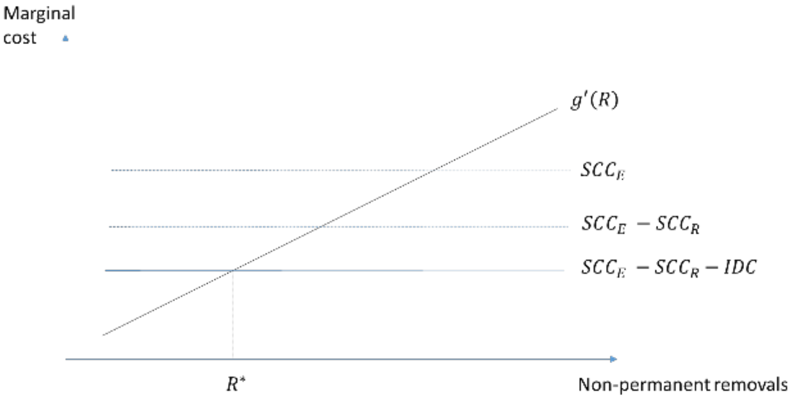


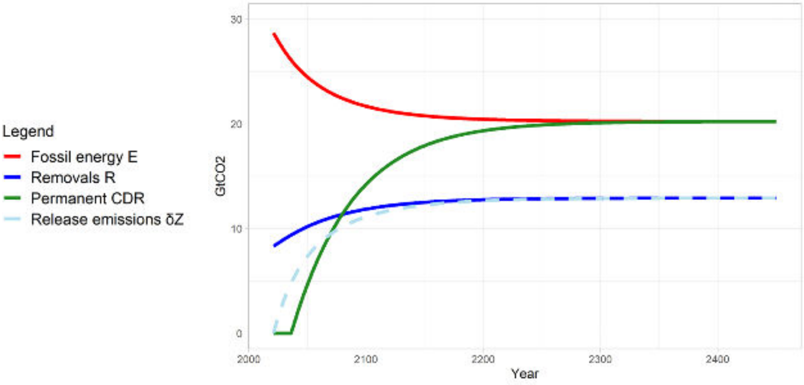
- Climate damage from **release emissions (SCC_R) and intertemporal diligence cost (IDC) lower the optimal amount** of non-permanent carbon removal

Agenda

Research aims

1. How to value non-permanent carbon dioxide removal?
2. **What’s the role of non-permanent carbon removal for long-run climate mitigation?**
3. How to design policy instruments for non-permanent removal?

Long-run steady state: Sisyphus' Warning



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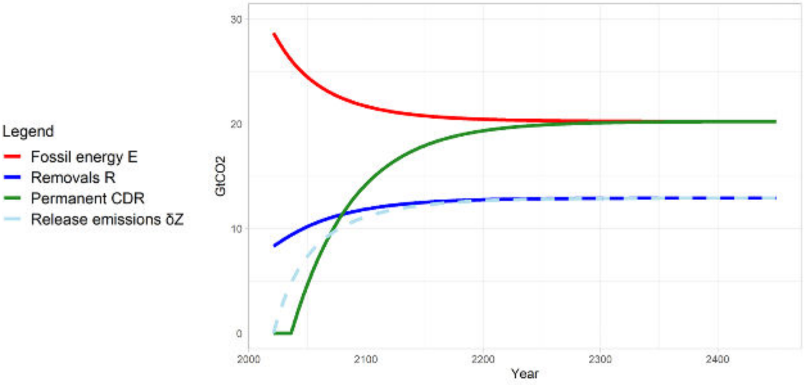

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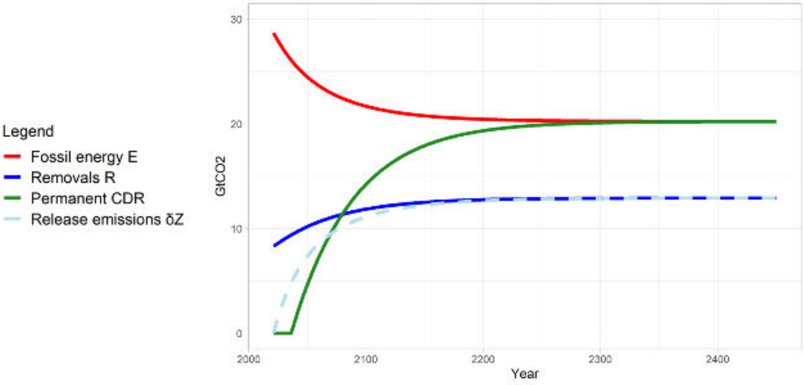

- Fossil emissions E are entirely offset by permanent removal P
- Non-permanent removal R converges towards the flow of released emissions $\delta_i^s Z^s$ (Sisyphus)

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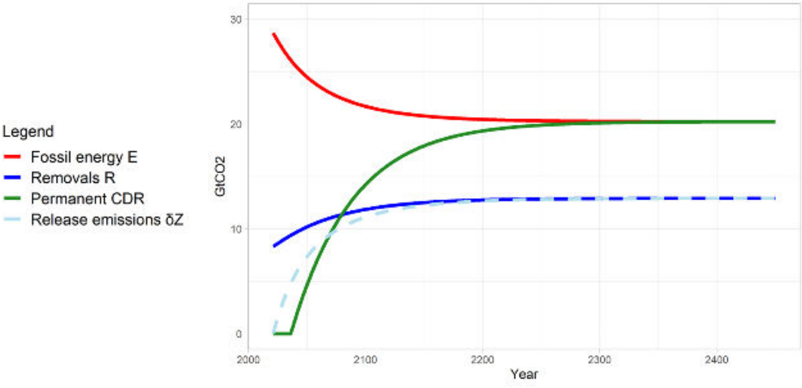

Steady state:

$$f'(E) = h'(P) = \frac{d'(X^s)}{r}$$

$$E = P$$

$$R_i{}^s = \delta_i^s Z_i^s$$

$$g'(R^s) = \frac{d'(X^s) + w_i(\delta_i^s)}{r + \delta_i^s}$$

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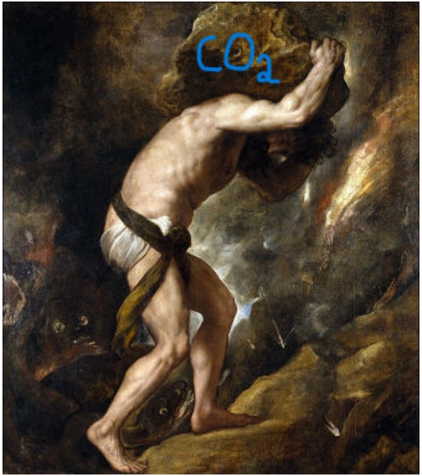
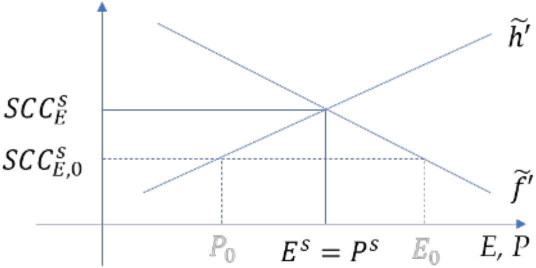
Titian (1548): *Sisyphus* (adapted)

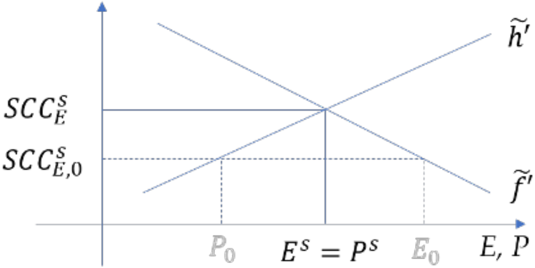


Long-run climate ambition



- The long-run climate ambition (long-run marginal climate damages) depend on the marginal cost of permanent removal $\tilde{h}'$, and on the marginal benefits of energy $\tilde{f}'$.

Long-run climate ambition



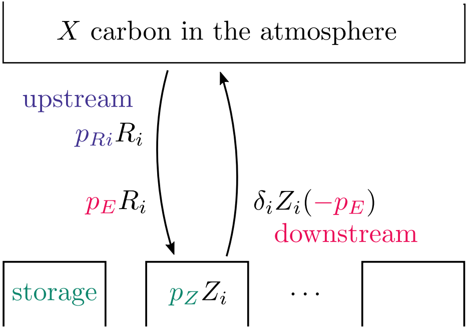
- The long-run climate ambition (long-run marginal climate damages) depend on the marginal cost of permanent removal $\tilde{h}'$, and on the marginal benefits of energy $\tilde{f}'$.
- Non-permanent carbon removal has **no impact on the long-run climate target**!

Agenda

Research aims

1. How to value non-permanent carbon dioxide removal?
2. What's the role of *non-permanent* carbon removal for long-run climate mitigation?
3. **How to design policy instruments for non-permanent removal?**

Policy Instruments: Pigou's Advice



X carbon in the atmosphere

upstream

$p_{Ri} R_i$

$p_E R_i$

$\delta_i Z_i (-p_E)$

downstream

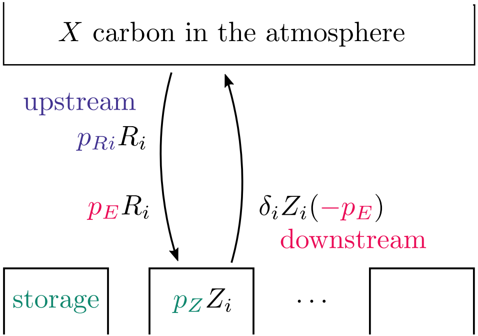
storage

$p_Z Z_i$

$\cdots$

- Three pricing schemes: upstream, downstream, or storage
- All achieve first-best deployment of non-permanent carbon removal

Policy Instruments: Discussion



1. Downstream: $p_E = SCC_E$
   - Requires monitoring of release emissions $\delta_i Z_i$

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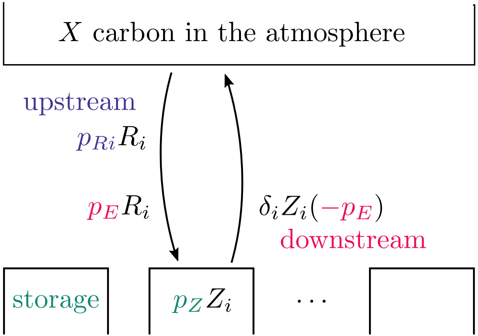

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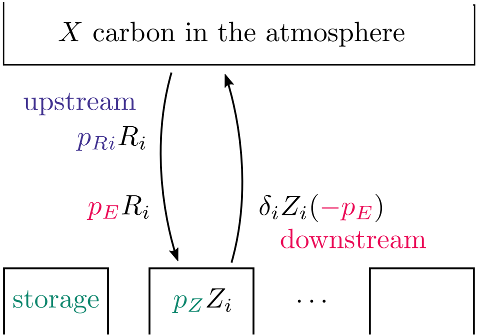

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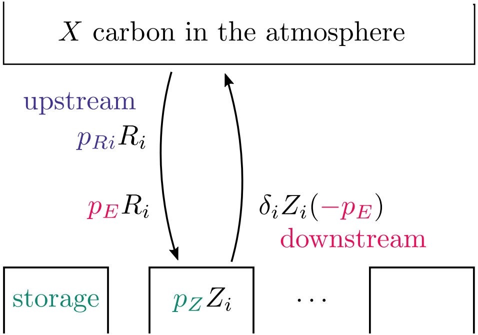

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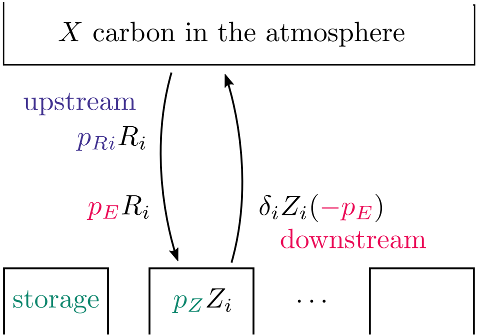
2. Upstream: $p_{Ri} = p_E - SCC_R = \lambda_i p_E$
   - $\lambda_i(t) \approx \lambda_i^S = \frac{r}{r+\delta_i}$

Policy Instruments: Discussion



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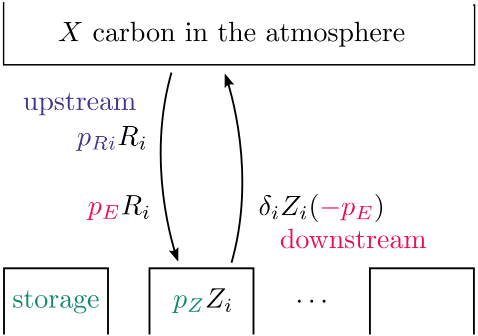

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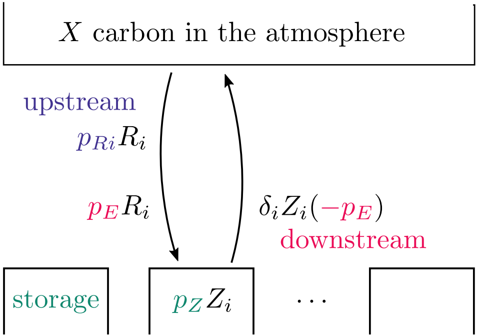

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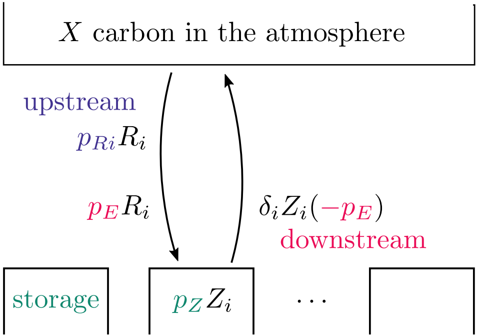
3. Storage subsidy: $p_Z = d'(X)$
    - Requires monitoring of storage Z_i

Policy Instruments: Discussion



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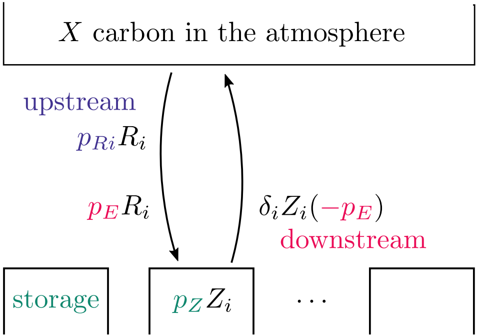

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   - Positive profits in the long-run
3. Storage subsidy: $p_Z = d'(X)$
   - Requires monitoring of storage Z_i
   - Incentivizes optimal diligence
   - Ambiguous if profitable in the long-run

Conclusion

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    - Social cost of carbon removal (SCC_{R_i})

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- Non-permanent removal cannot provide net-negative emissions in the long-run (Sisyphus)
    - No effect on long-term climate target
    - No effect on long-term carbon price

Conclusion

- Non-permanent removal entails intertemporal cost
  - Social cost of carbon removal (SCC_{R_i})
  - Intertemporal diligence cost (IDC_i)
- Non-permanent removal cannot provide net-negative emissions in the long-run (Sisyphus)
  - No effect on long-term climate target
  - No effect on long-term carbon price
- Policies need to consider
  - non-permanence
  - informational requirements, diligence incentives, and financial flows

Thank you!

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Appendix

Optimality Conditions

The first-order conditions of the planner's problem are

$$f'(E+N) = -\mu \tag{9}$$

$$f'(E+N) = b'(N) \tag{10}$$

$$g'(R) = \psi - \mu \tag{11}$$

$$\dot{\mu} = r\mu + d' \tag{12}$$

$$\dot{\psi}_i = r\psi_i + \delta_i(\psi_i - \mu) \tag{13}$$

$$0 = \lim_{t\to\infty} \mu(t)X(t)e^{-rt} \tag{14}$$

$$0 = \lim_{t\to\infty} \psi(t)Z(t)e^{-rt} \tag{15}$$

- μ - shadow price of the atmospheric carbon budget
- ψ_i - shadow price of the stored carbon stock by technology i

Steady State

In the **steady state**, there is no change in the state variables over time, i.e. $\dot{X} = 0 = \dot{Z}_i$. From the FOCs we obtain

$$\begin{aligned} E^s &= 0 \\ R_i^s &= \delta_i Z_i^s \\ f'(N) = b'(N) &= -\mu^s \end{aligned}$$

In addition, we find constant social cost of carbon in the steady state

$$\begin{aligned} \text{SCC}_E^s &= -\mu^s = \frac{d'(X^s)}{r} \\ \text{SCC}_{R,i}^s + IDC_i^s &= -\psi_i^s = \frac{d'(X^s)\delta}{r(r+\delta_i)} = -\mu^s \frac{\delta}{\delta + r} \end{aligned}$$

$\longrightarrow$ SCC_R and IDC are determined by the SCC_E and a factor $\gamma = \frac{\delta}{\delta+r} < 1$

Comparative Statics for R^s

Assuming quadratic climate damages, backstop and removal cost allows to derive **comparative statics for** R^s

$$\frac{\partial R^s}{\partial r} > 0, \qquad \frac{\partial R^s}{\partial \delta} < 0,$$
$$\frac{\partial R^s}{\partial b_0} > 0, \qquad \frac{\partial R^s}{\partial g_0} < 0$$

Optimal removal quantities R^s in the steady state

- decrease in leakage rates δ
- decrease in marginal removal cost g_0

Comparative Statics for X^s

Assuming quadratic climate damages, backstop and removal cost allows to derive **comparative statics for X^s**

$$\frac{\partial X^s}{\partial r} > 0, \qquad \frac{\partial X^s}{\partial \delta} = 0,$$

$$\frac{\partial X^s}{\partial b_0} > 0, \qquad \frac{\partial X^s}{\partial d_0} < 0$$

$$\frac{\partial X^s}{\partial g_0} = 0$$

$\Longrightarrow$ The long-run temperature level (and thus the long-run SCC-E) is independent from cost g_0 and leakage δ properties of carbon removal

$\Longrightarrow$ Backstop cost b_0 are decisive for determining the long-run temperature level

Decentralized Economy: Downstream Carbon Pricing

Households maximize

$$\max_{E,R_i} \int_0^\infty \left[f(E) + y - p_E \left(E + \sum_i (\delta_i Z - R_i) \right) - \sum_i g_i(R_i) - bN + \Gamma \right] e^{-rt}$$

subject to their budget constraint $y = p_E \left(E + \sum_i (\delta_i Z - R_i) \right) + \sum_i g_i(R_i) - \Gamma$ where Γ are lump-sum transfers that correspond to the revenues from carbon pricing. Households also consider the removed carbon stocks and the emissions that leak from them as they are subject to carbon pricing;

$$\dot{Z}_i = R_i - \delta_i Z_i \tag{16}$$

FOCs

$$f'(E) = p_E \tag{17}$$

$$g'(R_i) = p_E + \tilde{\psi}_i \tag{18}$$

$$\dot{\tilde{\psi}}_i = (r - \delta_i)\tilde{\psi}_i + \delta p_E \tag{19}$$

$$0 = \lim_{t \to \infty} \tilde{\psi}_i(t) Z_i(t) e^{-rt} \tag{20}$$

Decentralized Economy: Upstream Carbon Pricing

Households maximize

$$\max_{E,R_i} \int_0^\infty \left(f(E) - \sum_i g_i(R_i) - p_E E + \sum_i p_{R,i} R_i \right) e^{-rt} dt$$

subject to their budget constraint $y = p_E E + \sum_i p_{R,i} R_i - \Gamma$ where Γ are lump-sum transfers that correspond to the revenues from carbon pricing net of potential subsidies to carbon removal. The FOCs are

$$f'(E) = p_E \tag{21}$$

$$g'(R_i) = p_{R,i} \tag{22}$$

With $p_E = -\mu^* > 0$ and $p_{R,i} = -\mu^* + \psi_i^*$, the optimality conditions equal those of the social planner.