A Model for Global Cooperation on Climate Change: Dynamic Lindahl Equilibrium under Uncertainty

Markku Kallio, Iivo Vehviläinen, and Hanna Virta

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Aalto University & Helsinki Graduate School of Economics
markku.kallio@aalto.fi, iivo.vehvilainen@aalto.fi

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"Here, in Paris, we can show the world what is possible when we come together, united in common effort and by a common purpose."
— Barack Obama, speaking at COP21

Research motivation

1. What is possible through cooperation?

2. What are the implications of uncertainty?

This paper

Theory

- Uses Lindahl's solution to the allocation of a public good
- Extends early results to a dynamic setting with multiple stakeholders and uncertainty

Quantification ($\leftarrow$ focus today)

- Nordhaus' RICE-model with a cooperative solution concept
- Includes uncertainty in key climate and economic parameters
- Explores the value of negative emissions technologies

Key takeaways

- Possible that cooperation benefits *all* regions in the long run
- Poorer regions gain most from cooperation in relative terms through
  1. lower damages
  2. equilibrium compensations
  3. a more balanced sharing of abatement costs
- In catastrophic climate outcomes, backstop technology becomes necessary
  - In expectation its present "insurance" value is measured in trillions of U.S. dollars $\rightarrow$ makes sense to invest in R&D

Lindahl’s equilibrium

Lindahl's equilibrium (Lindahl, 1919)

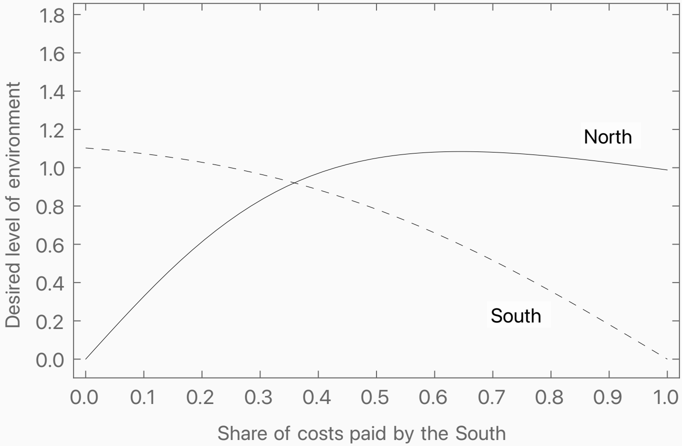


Figure 1: Willingness to pay for cleaning up a river

Lindahl's equilibrium – Climate application

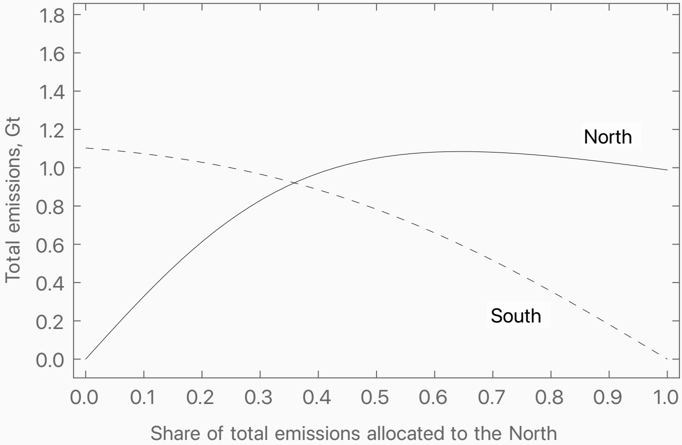


Figure 2: Willingness to pay for emissions.

Lindahl's equilibrium – Climate application

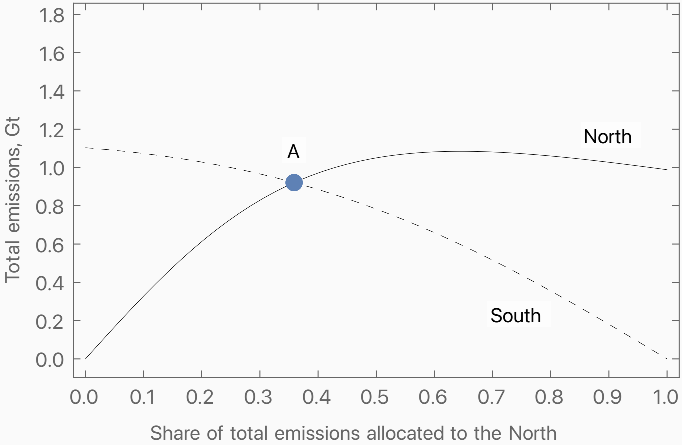


Figure 3: A = cooperative equilibrium without transfers

Lindahl's equilibrium – Climate application

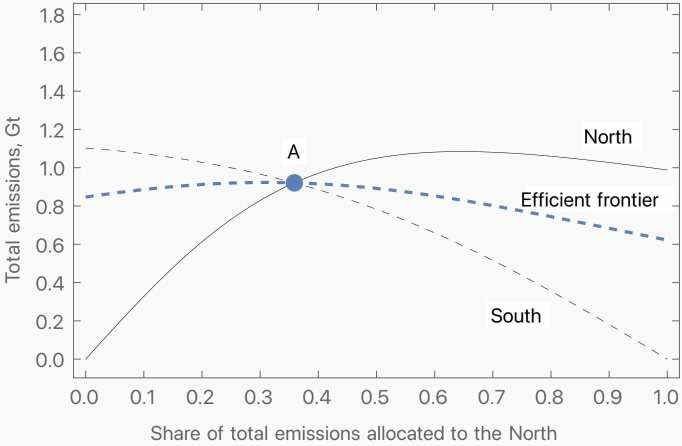


Figure 4: Efficient frontier = social planner's choice of total emissions

Lindahl's equilibrium – Climate application

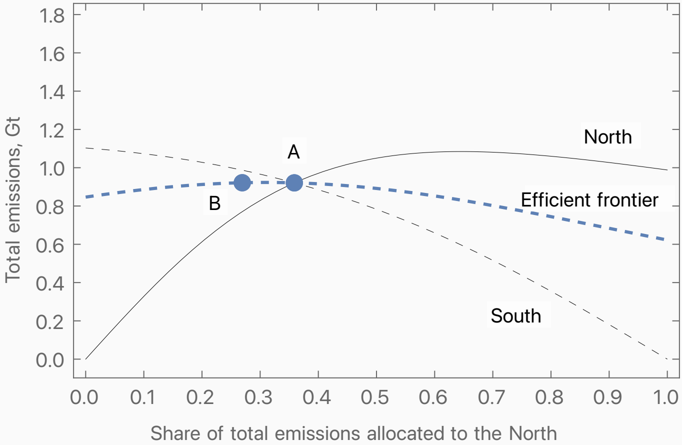


Figure 5: B = efficient solution = Lindahl's equilibrium

Lindahl's equilibrium – Climate application

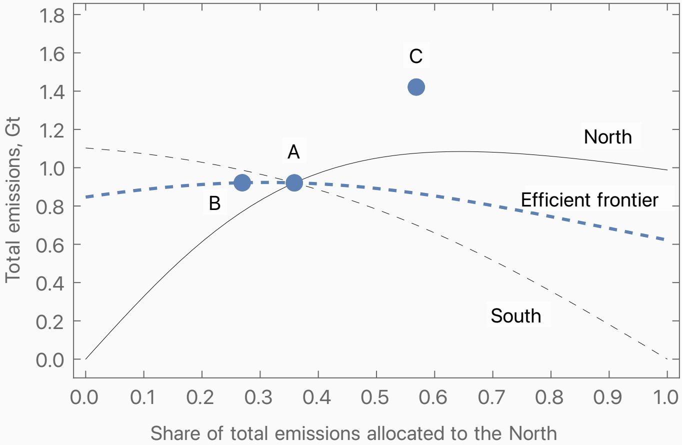


Figure 6: C = Cournot–Nash allocation

More general climate–economy model

- World subdivided to N regions, $i = 1, 2, \ldots, N$, observed in states n at discrete times $t = 0, 1, 2, \ldots, T$
- One consumption good whose consumption c_{in} gives utility $u_{in}(c_{in})$
- Production of the good $y_{in} = y_{in}(e_{in}, x_n, k_{in}, l_{in})$
- State of the global environment evolves according to

$$x_n = M(x_{n\_}) + fe_n = 0$$

- Financial market and tradable permit market

Generalized Lindahl's equilibrium for the climate problem

- Regional emissions deteriorate the state of the global environment
- Agree on the effort level: how much to reduce global emissions
- Allocate the effort via personalized prices
  - Carbon tax: P_n is the price that region i pays for its emissions e_{in}
  - Compensation: P_{in} for region i for the global emissions e_n
- Solution strategy:
  - Start with regional welfare maximization
  - Formulate a global problem whose solution yields optimal regional policies and is a Lindahl's equilibrium
  - Use stochastic programming to solve the equilibrium conditions

Global problem for computing a Lindahl equilibrium

Given some weights $\lambda_i > 0$, the *global problem* is to find, for all i and n,

- consumption c_{in}, output y_{in} and emissions e_{in},
- global environmental state x_n, and
- capital investments z_{in} and capital stock k_{in}, to

$$\max \sum_i \lambda_i \sum_n \pi_n \rho_{in} u_{in}(c_{in})$$

subject to

$$\sum_i (\ c_{in} + z_{in} - y_{in} \ ) = 0 \qquad (d_n)$$

$$-x_n + M(x_{n_-}) + f \sum_i e_{in} = 0 \qquad (\mu_n)$$

$$k_{in} - \delta_k k_{in_-} - z_{in} = 0 \qquad (\nu_{in})$$

Lindahl's equilibrium: Existence

Consider an optimal solution for the global problem.
For all i and n, define

$$P_n d_n = \mu_n f \tag{1}$$

$$P_{in} d_n = \mu_{in} f \tag{2}$$

$$\Delta_{in} = c_{in} + z_{in} - y_{in} + P_n e_{in} - P_{in} e_n \quad \text{[deficit]} \tag{3}$$

$$r_i = \sum_n d_n \Delta_{in} \quad \text{[npv via stochastic discounting]} \tag{4}$$

Theorem

Given definitions (1)–(4), if the npv $r_i = 0$, for all i, then
(i) *the optimal global solution provides optimal local solutions*
by choosing financial asset positions to balance regional budgets;
(ii) *such optimal regional solutions constitute a Lindahl equilibrium.*

Lindahl's equilibrium: Existence

Final step is to find regional weights, λ_i, in global problem so that:

1. regions reach unanimity on preferred global emissions
2. local production decisions are consistent with global emissions
3. net emission charges sum up to zero, and
4. financial positions are globally balanced.

As in Negishi (1972) for the welfare theorems, we construct an iterative algorithm for computing λ_i and prove existence through Bouwer's fixed point theorem.

Integrated assessment model

We build on RICE-2020

1. Stylized model for the economy offers a well-known starting point with a calibrated regional data set (Nordhaus & Yang, 2021)

2. We update climate sensitivity according to the latest scientific understanding (e.g., Barnett, Brock, Hansen, 2022)

3. We use more stringent exponential economic damages from warmer temperatures (akin to Weitzman, 2009)

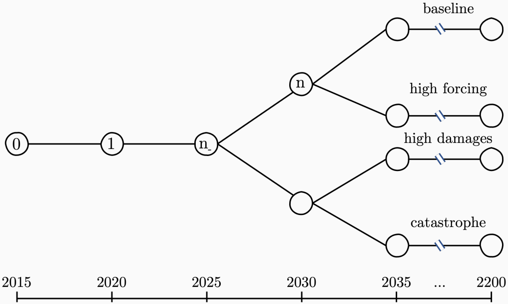
Key changes

1. **Uncertainty.** Our model incorporates a range of future outcomes that vary key uncertainties.

2. **Cooperative solution.** Negishi iterations where each iteration solves the global climate–economy model over time and states of the world.

3. **Backstop technology.** We explore Direct Air Capture, a negative emissions technology.

Uncertainty



	prob.	forcing	damages
baseline	.33	1	1
high forcing	.33	1.3	0.5
high damages	.33	0.7	1.5
catastrophe	.01	1.6	2.0

- Four scenarios that capture key uncertainties
- Increment factors of damages and forcing are relative to baseline

Backstop technology

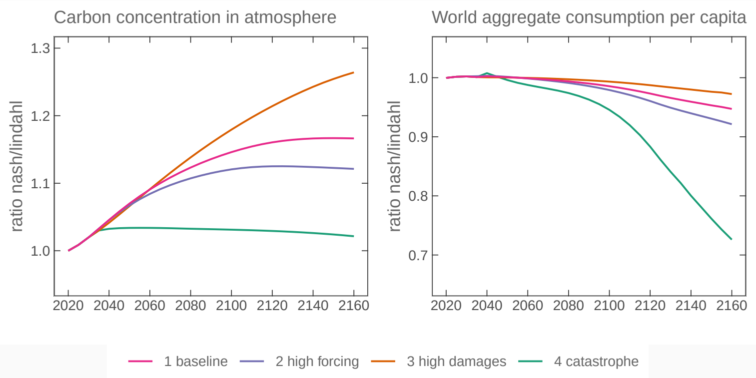
Direct air capture, DAC:

> “If the goals for climate and economic growth are to be achieved, negative emissions technologies will likely need to play a large role in mitigating climate change by removing 10 Gt/y CO2 globally by midcentury and $\sim$ 20 Gt/y CO2 globally by the century's end.”

—National Academies of Sciences, Engineering, and Medicine (2019). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.

Results

Cournot-Nash vs. Lindahl

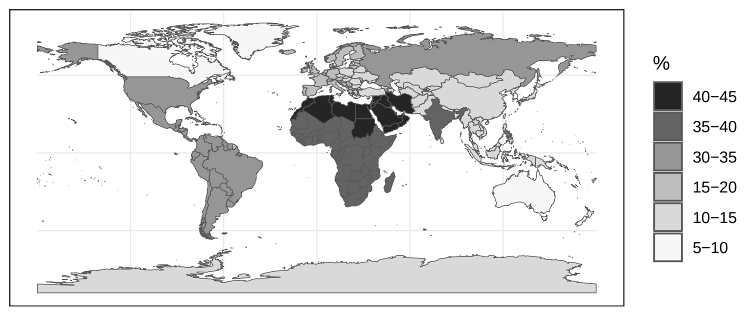


Left: Competing regions consume and emit more initially...

Right: ...which later leads to fall in welfare, especially if we get a bad draw from uncertain climatic future.

Beneficiaries of cooperation: Lindahl over Nash

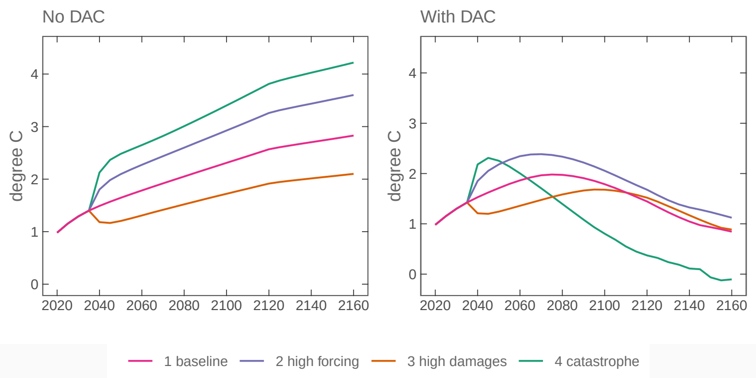
Relative annual expected gain (compared to GNI per capita, PPP)



1. Poorest regions saved from worst impacts of climate change
2. Equilibrium compensations
3. More even burden sharing

Impact of Direct Air Capture (DAC) to temperatures

Cooperative solutions:

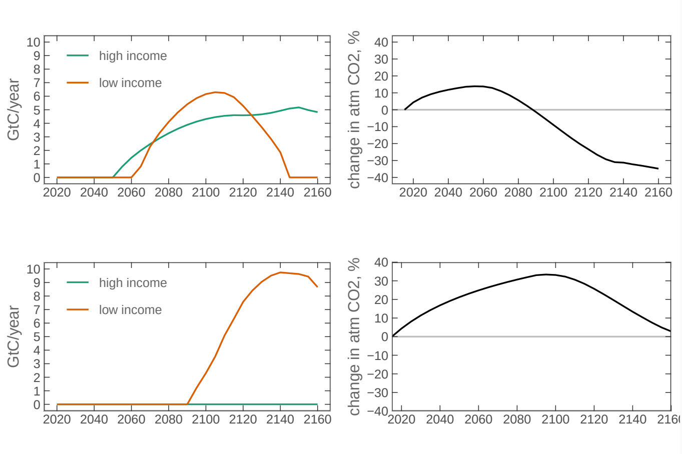


Left: Even ambitious reductions in emission/output ratios insufficient

Right: Backstop technology needed, esp. in catastrophic outcomes

Use of DAC

Cooperation (Top) vs. non-cooperation (Bottom)



→ High income countries free-ride at the cost of others in the non-cooperative world

Back to the climate negotiation table

- Lindahl's solution exits, and offers benefits for all regions
- Investing to backstop technologies now to have them in place later reduces uncertainty of future costs
  - Value of negative emissions technology $8 trillion with conservative valuations of future damages (3% discount rate)
  - Caveats apply: What if the technology never works?
- Well-off countries could proxy the cooperative solution by offering to develop new radical technologies to contain damages (à la Kremer's ideas on vaccinations)

UN Photo/Eskinder

"The Paris Conference should reject the narrow-minded mentality of "zero sum game" and call on all countries, the developed countries in particular, to assume more shared responsibilities for win-win outcomes."
— Xi Jinping, speaking at COP21