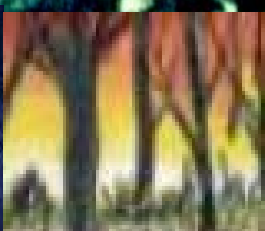
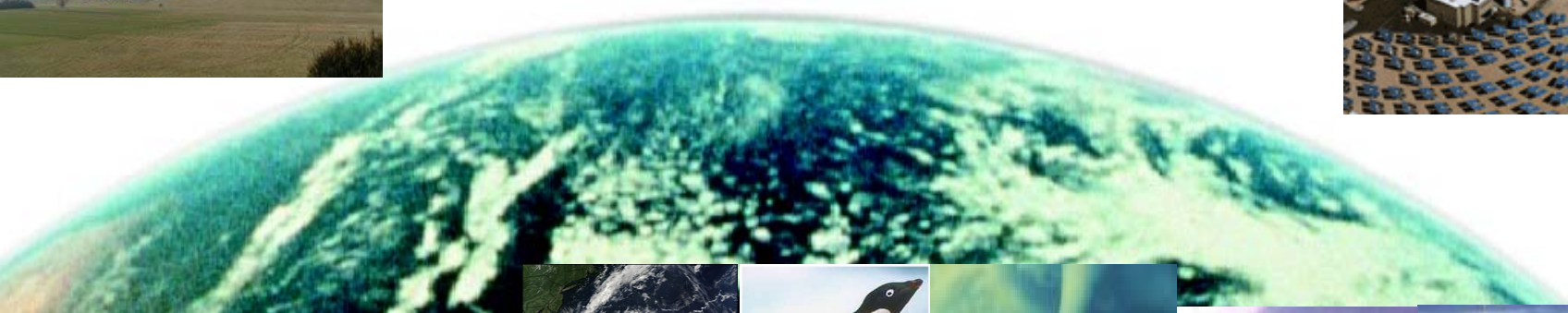


# Adaptive Management and Multi-Region Cooperation for Low-Carbon Stabilization

**Jürgen Scheffran**

University of Illinois, Urbana-Champaign  
In collaboration with Gopi Rethinaraj, Michael  
Schlesinger, Clifford Singer and Bin Li

Low Stabilisation Scenarios  
Strategies Technologies and Costs  
Joint Workshop of PIK and FEEM,  
Potsdam, 16-17 March 2006.



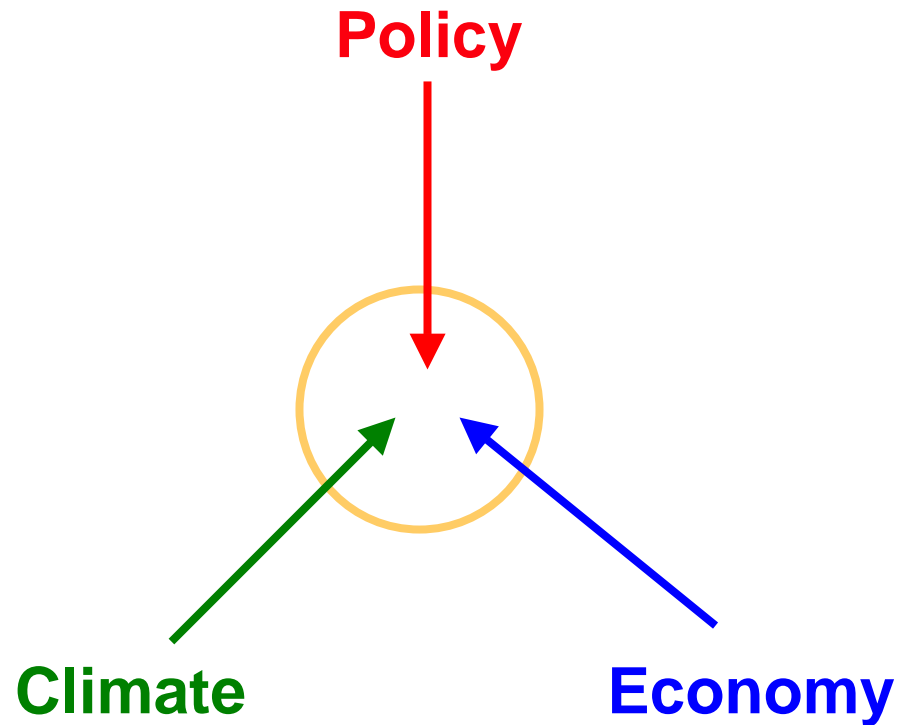
# Outline

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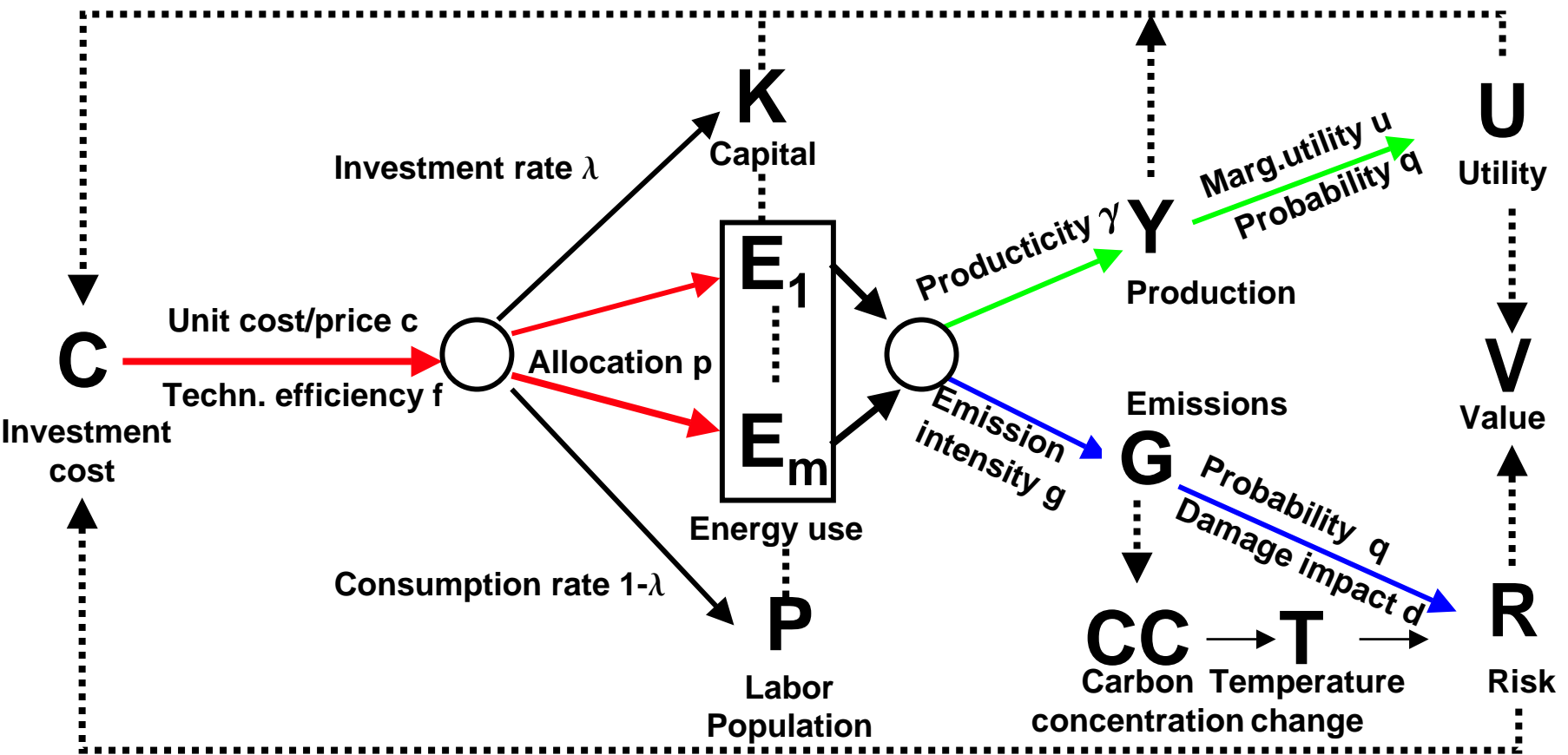
- 1. Integrated assessment and decision-making on energy and climate change**
- 2. Data, uncertainty and risk**
- 3. Adaptive strategies vs. optimal control**
- 4. Interactive decision-making, cooperation and coalition formation among multiple actors**
- 5. Summary and outlook**

# Integrated Approach

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# Integrated Decision-making on Energy Options



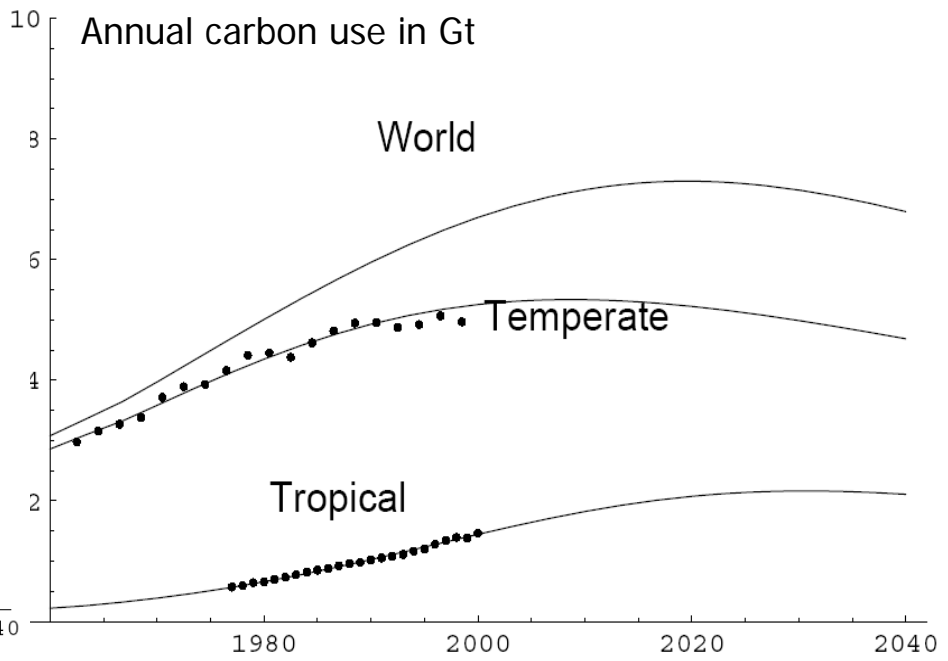
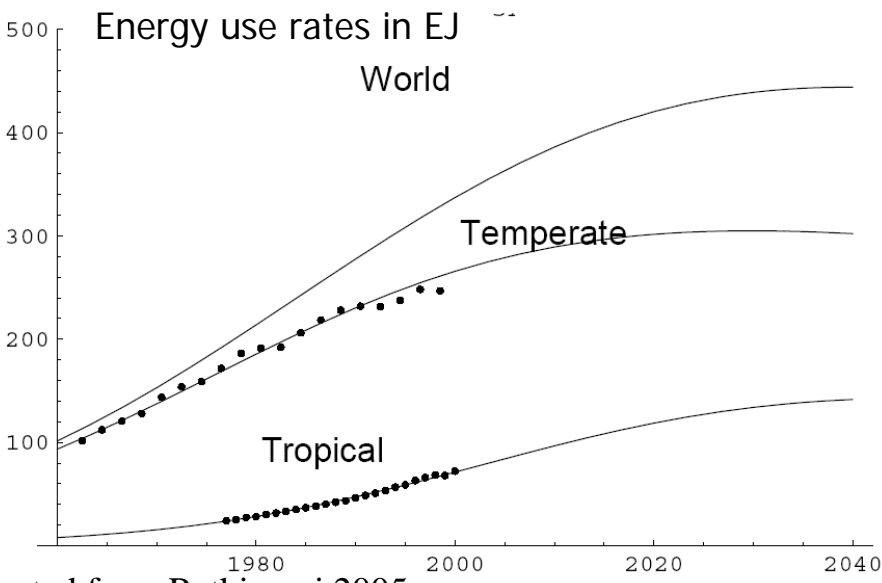
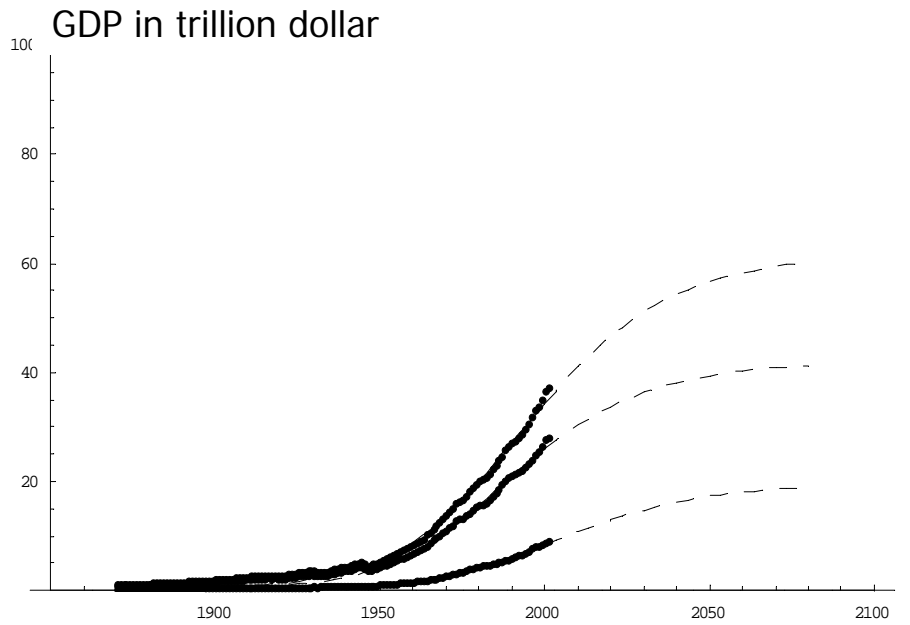
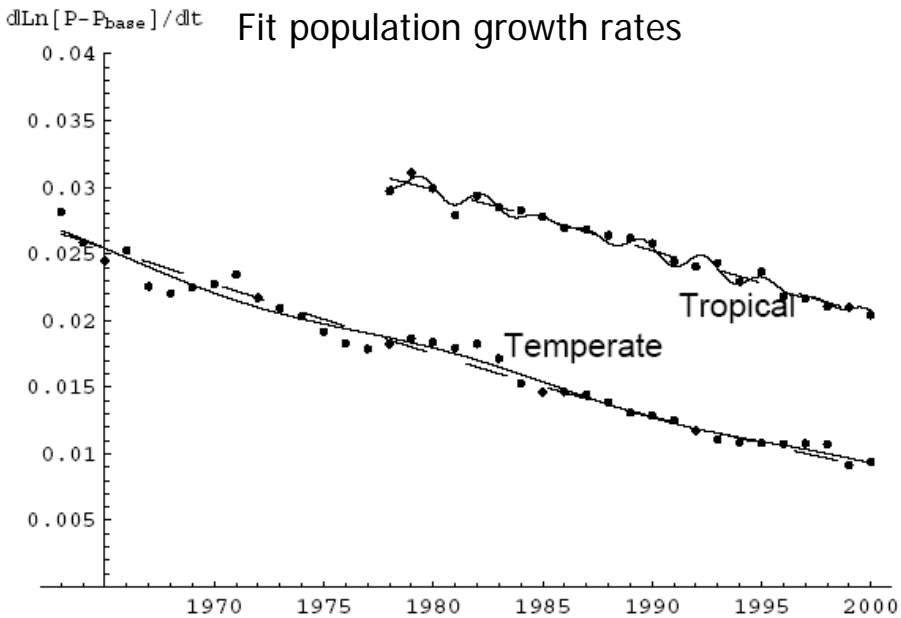
$$U(E) = p q f \gamma u C(E) / c$$

$$R(E) = q (D/G) (G/E) (E/Y) (Y/P) P = q d g e y P$$

# Data-calibrated Econometric Model with Reduced Climate Model

- Optimization of time-integrated discounted utility of per capita consumption using log-linear production functions in capital, labor, energy, and development with constant returns to scale.
- Energy production is log-linear in labor, capital, and development. Energy production, total capital and population are measured in units of their steady-state limits.
- Development index grows logistically with time in proportion to population and is the ratio of total labor to its steady-state limit. Population growth rates are used to calibrate the development index.
- Production efficiency decreases linearly with decreasing carbon intensity of energy production, which is data calibrated for the past and determined by theories of fuel source substitution and international cooperation on emissions limitations for more distant future.
- Country data and simulation results are clustered into different regional aggregations (tropical region within forty degrees north and south and temperate region).

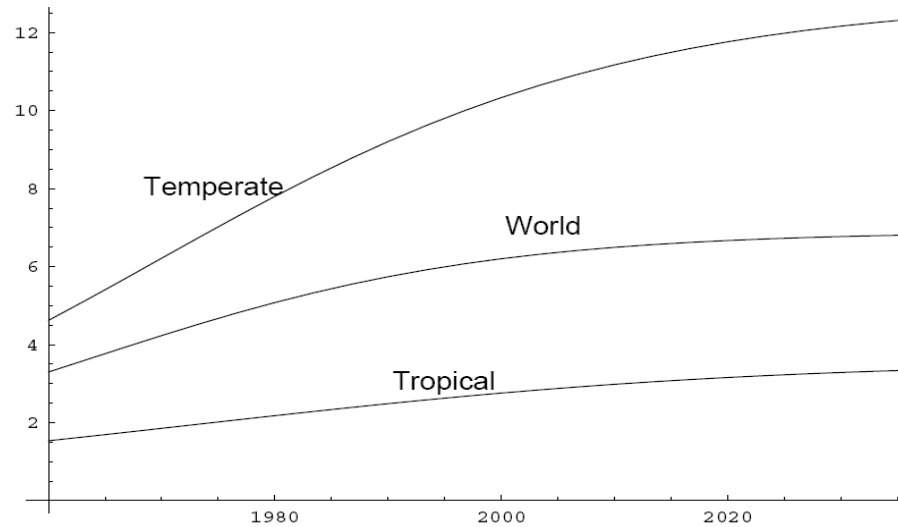
# Data and Projections for Population, GDP, Energy, Carbon



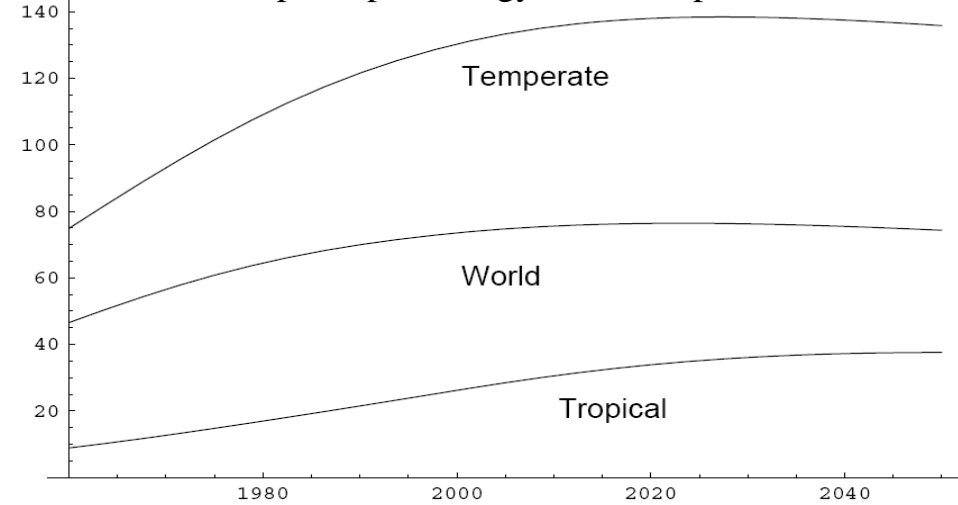
# Relevant Factors

Rethinaraj 2005

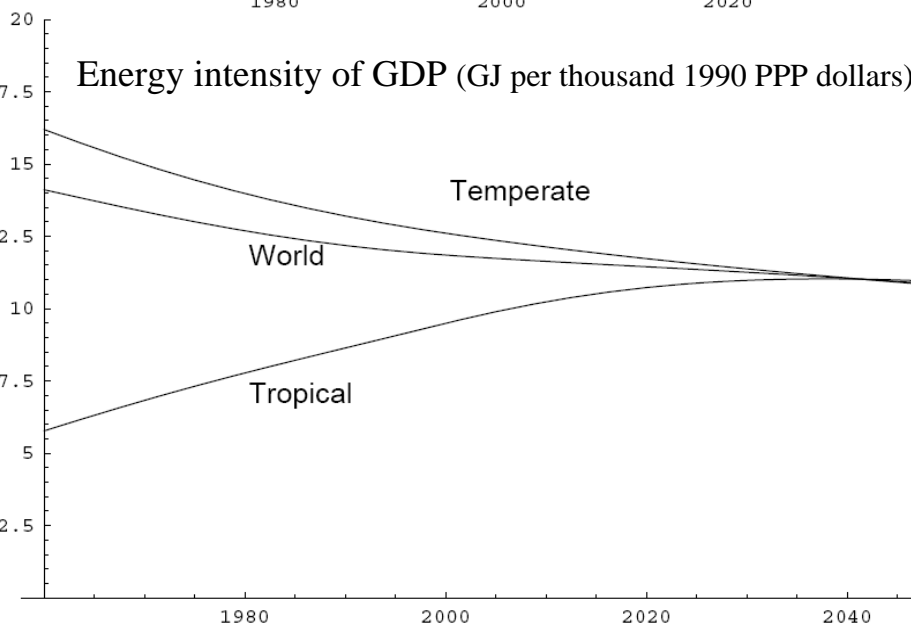
Annual GDP per capita in thousand 1990 dollars/person



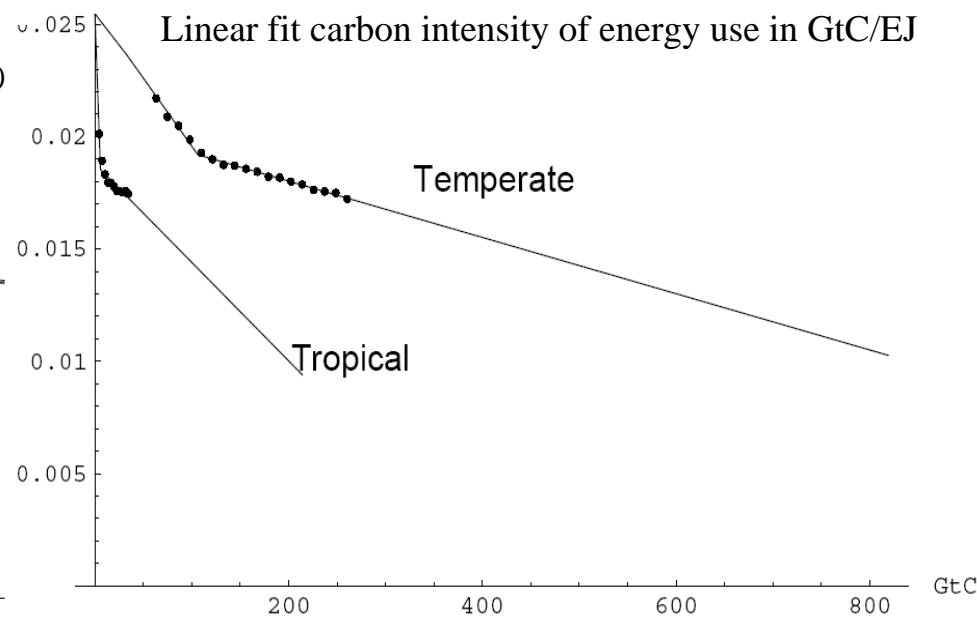
Annual per capita energy use in GJ/person



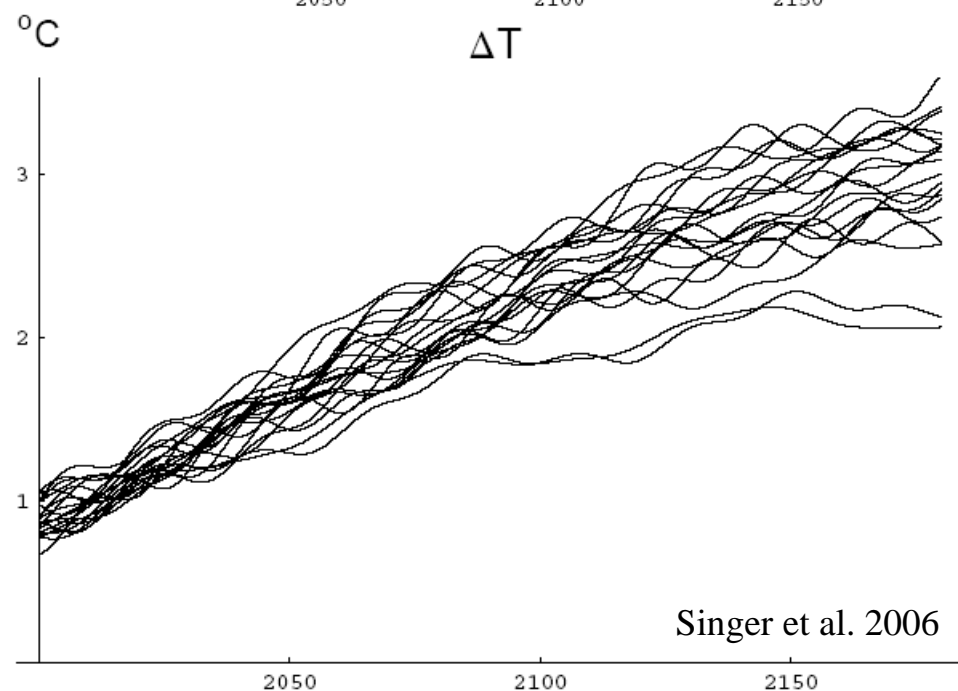
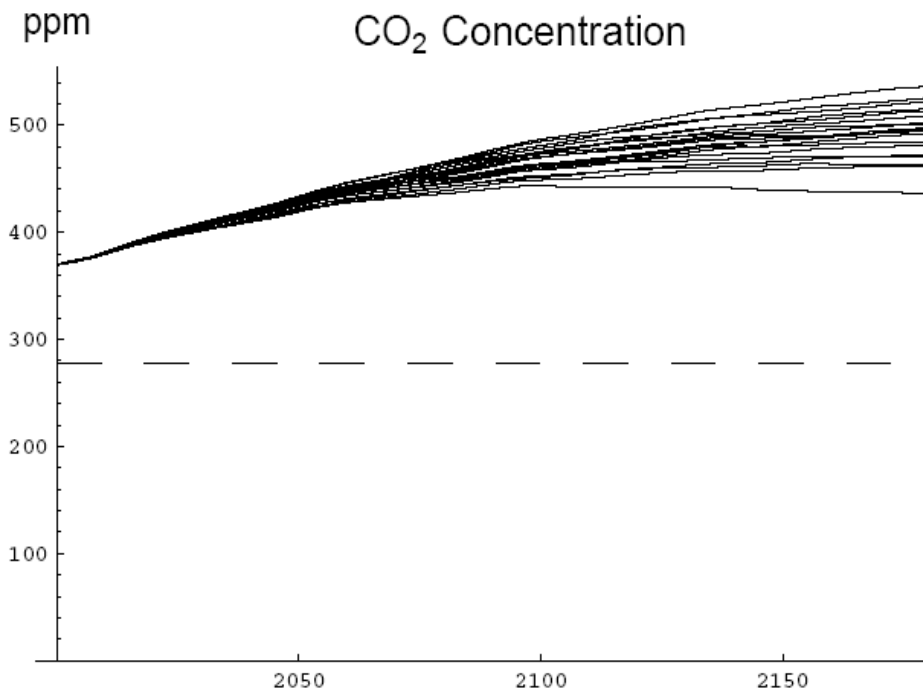
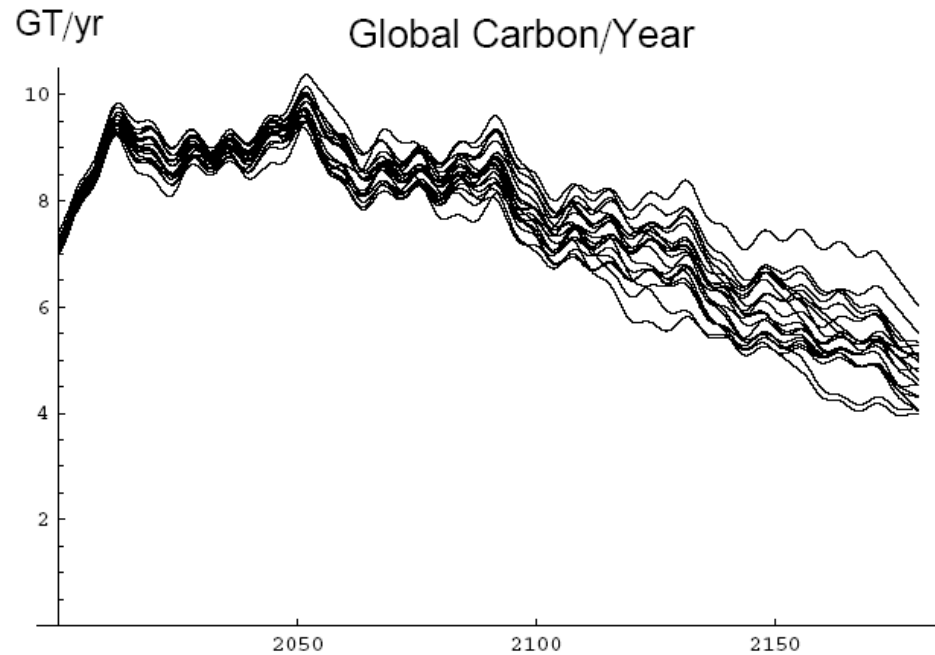
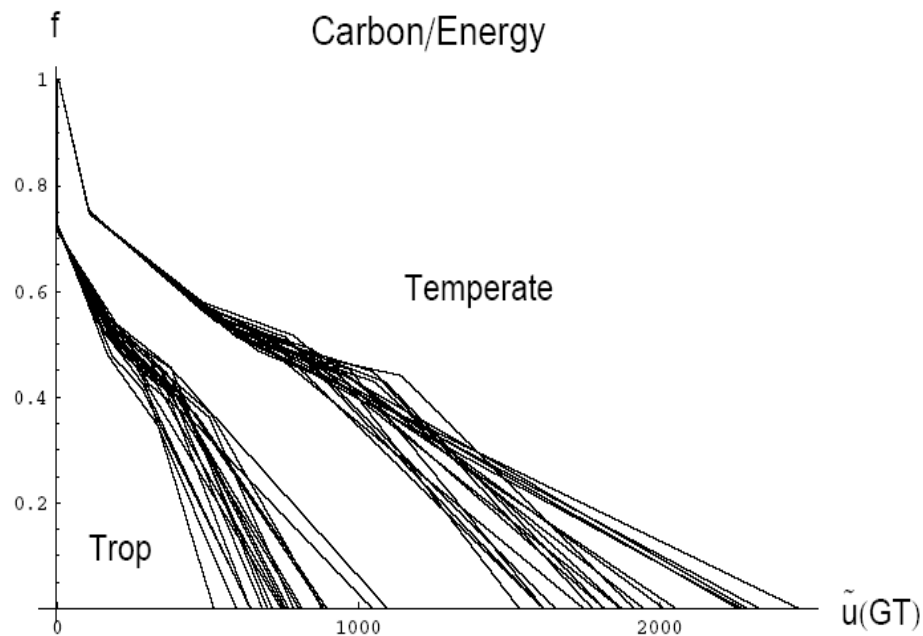
Energy intensity of GDP (GJ per thousand 1990 PPP dollars)



Linear fit carbon intensity of energy use in GtC/EJ

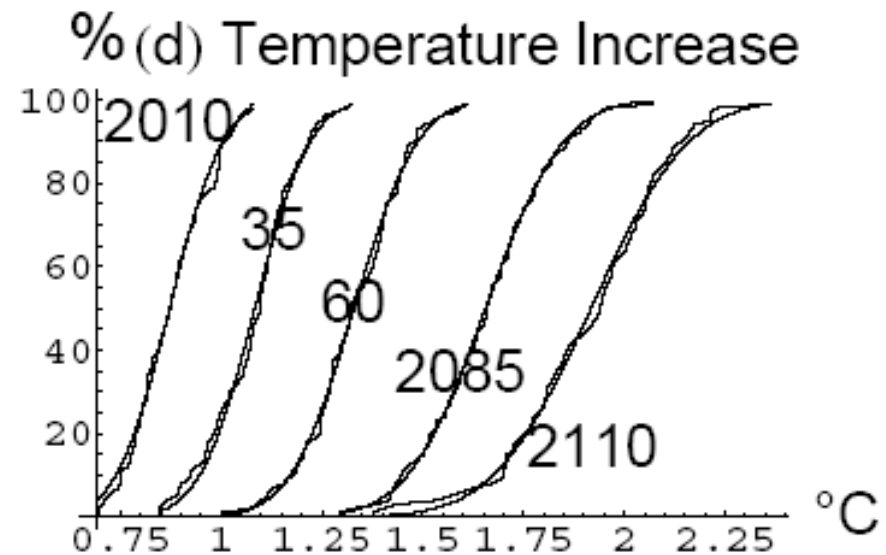
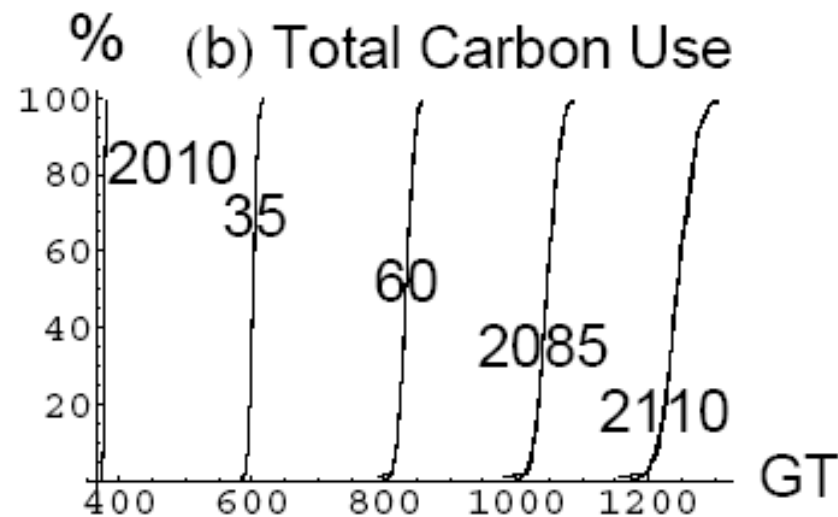
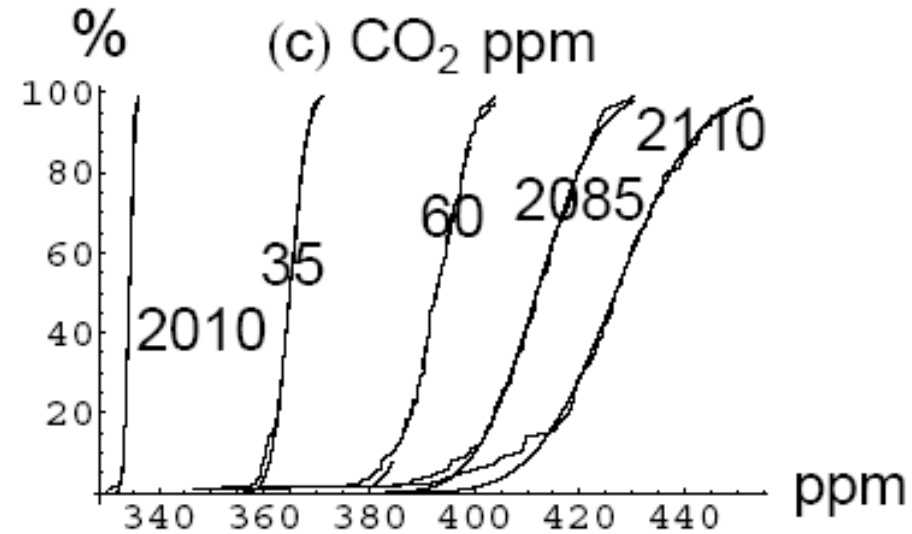
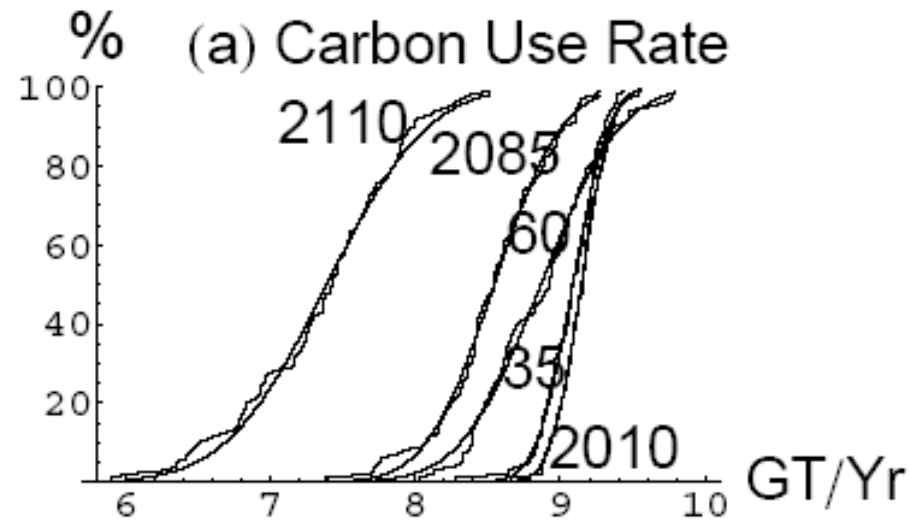


# Randomly Sampled Climate Variables

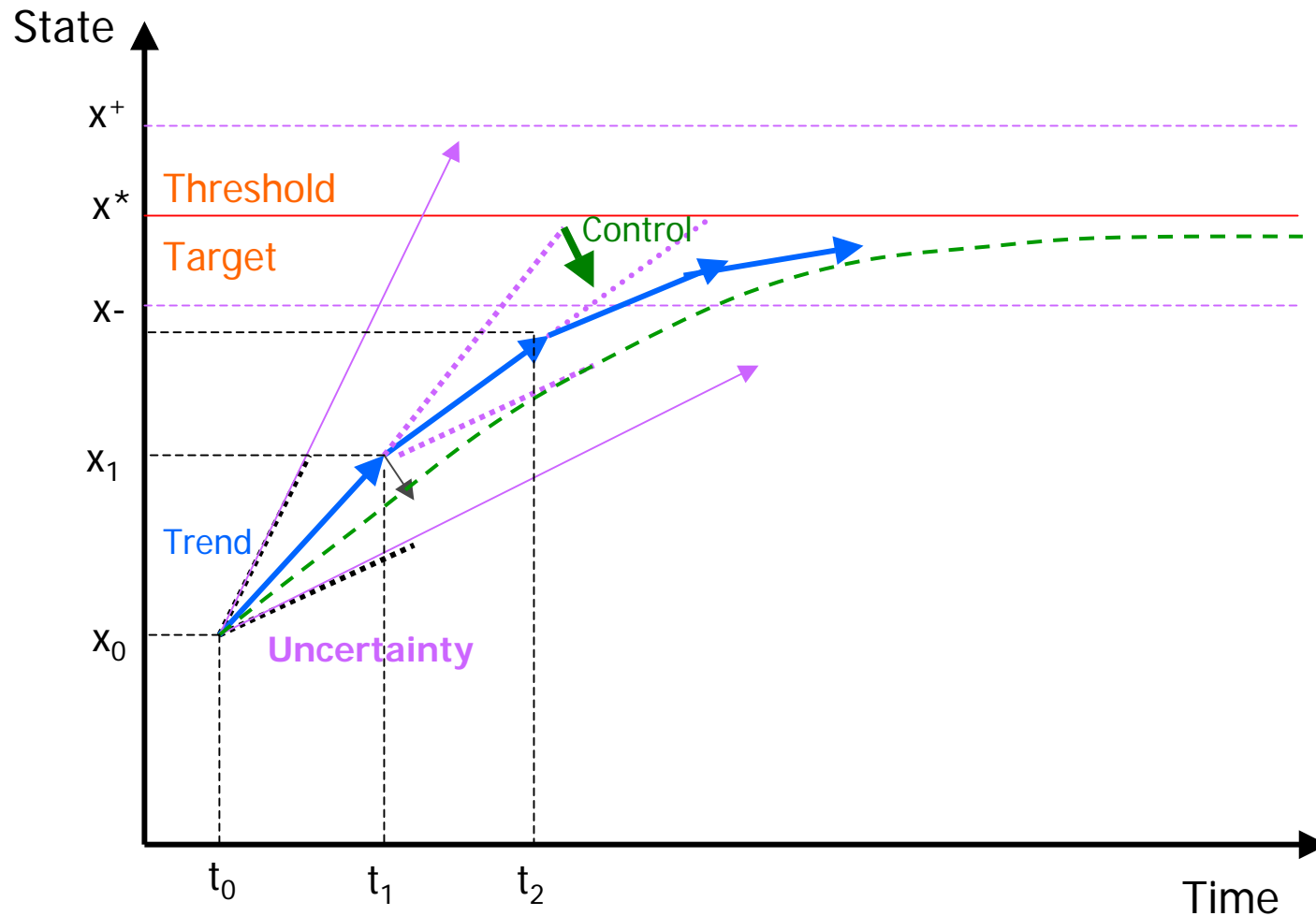


# Cumulative Probability Distributions

Cumulative probability distribution centiles (jagged plots), and cumulative normal distributions fit to central 95 centiles (smooth curves) for indicated years (Singer et al. 2006)



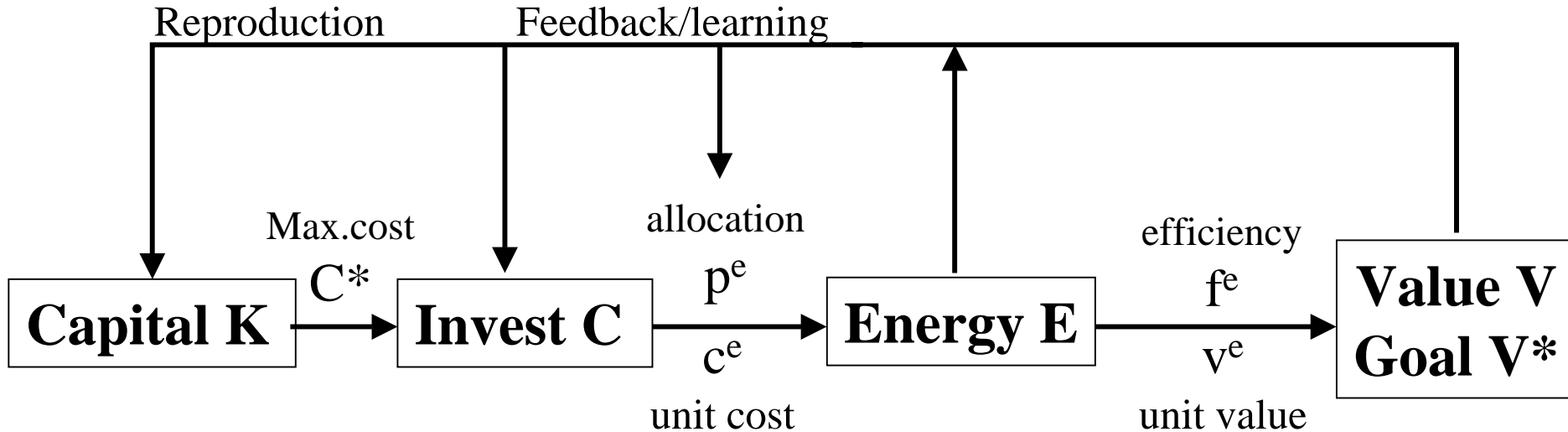
# Adaptive Control Under Uncertainty



Adaptive decision rules:  $\Delta x(t) = \omega(x, t) D(x, t)$

Speed control  $\Delta x(t) \leq \omega (x^*(t) - x(t))$

# The single actor feedback loop



$$\Delta V = v^e \Delta E = f^e C$$

$$\Delta C = -k C (C^* - C) (V - V^* + \tau \Delta V)$$

Logistic budget restraint

Value driver

**C** : Cost invested in a given period (flow variable) for changing system state  $x$  with

$f^x = p^x v^x / c^x$  action efficiency, depending on unit cost  $c^x$ , unit value  $v^x$  and

$p^x$  : percentage of cost allocated to action path  $x$ .

**k** cost reactivity in logistic reaction function

$\tau$  desired decay time of value gap

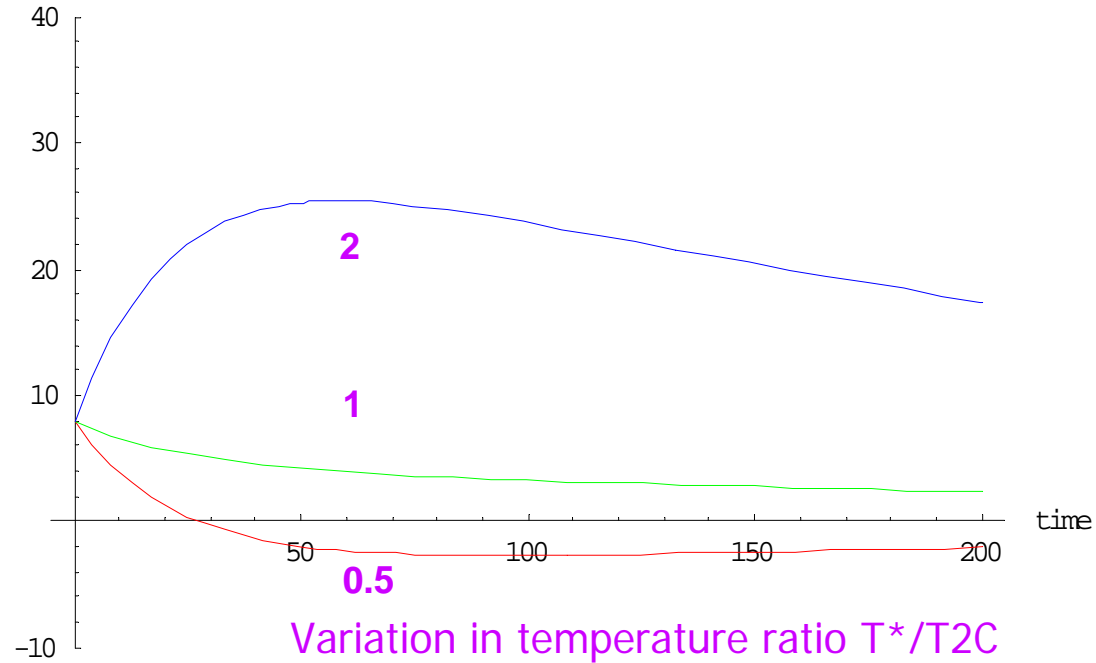
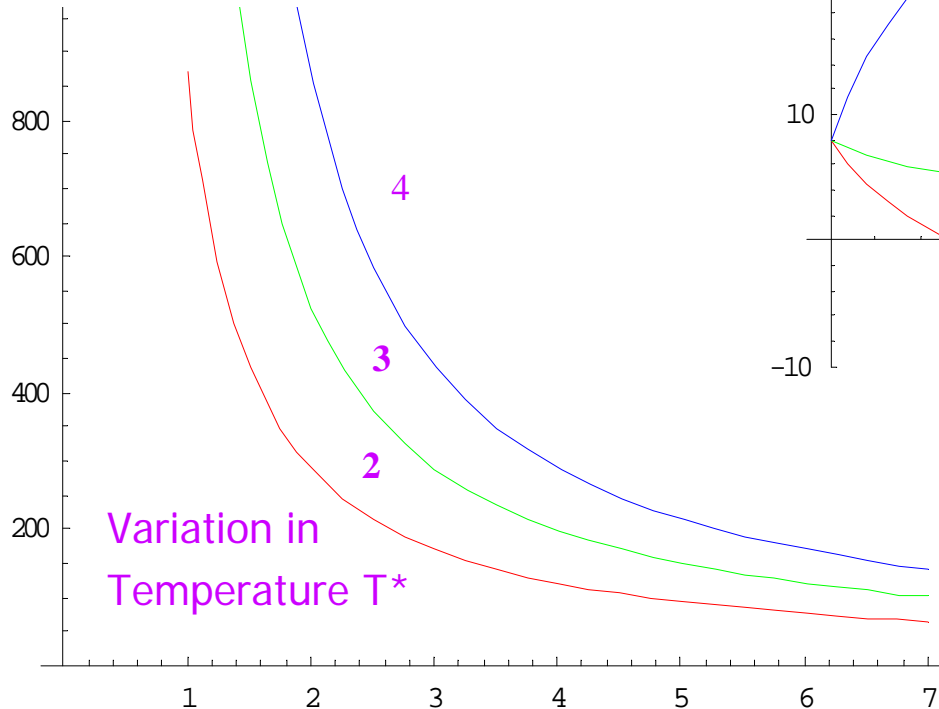
$$0 \leq C \leq C^*$$

# Carbon Limits and Adaptive Emission Rates

Temperature limit  $\Delta T(t) \leq w (T^*(t^*) - T(t))$ ,  $T(t) = T^* - (T^* - T^0) e^{-wt}$

Admissible emission rate in GtC/yr

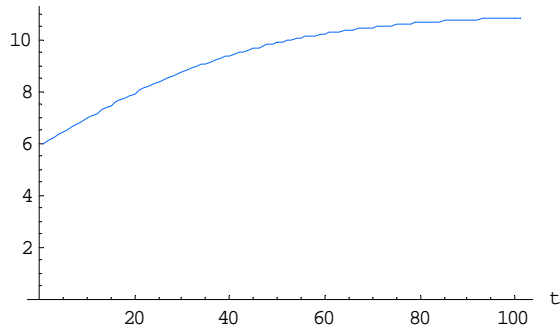
Atmospheric carbon limit [ppm]



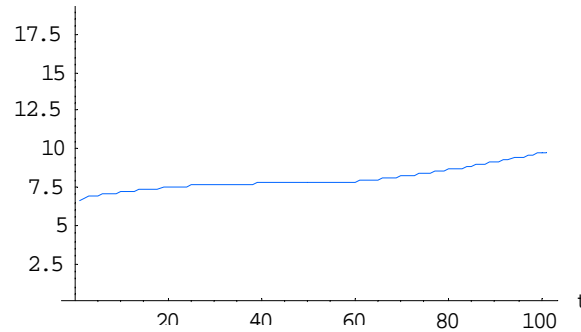
Climate Sensitivity [°C]

# Technical Change and Climate Damage

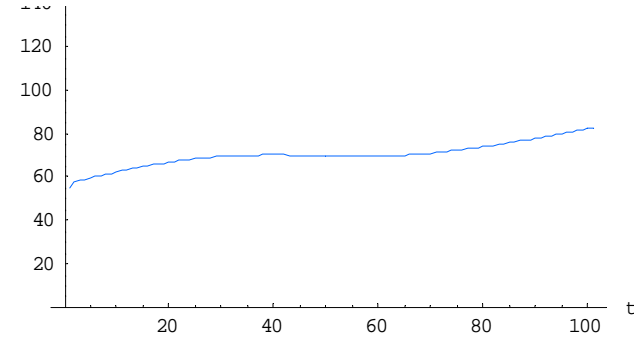
Population in bio.



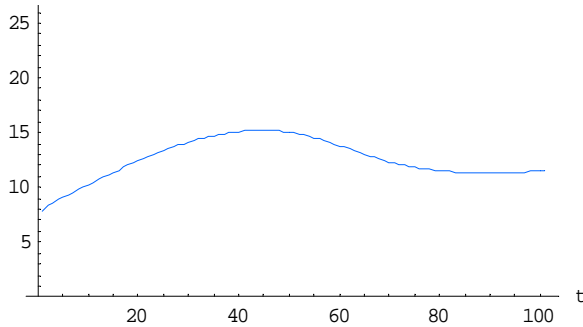
Production/capita in \$10,000



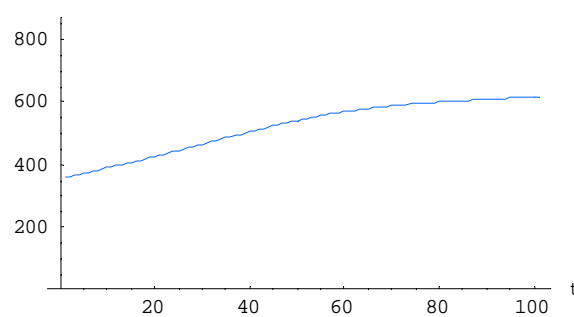
Energy/capita in GJ



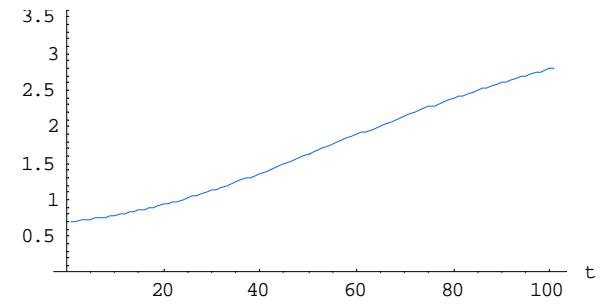
Emissions in GtC/a



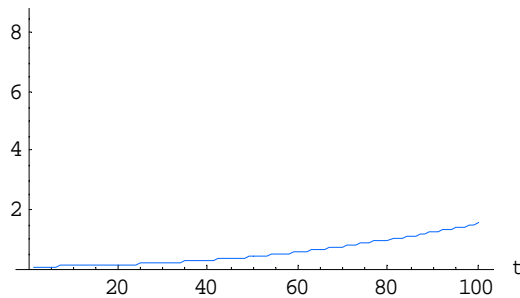
Atmospheric carbon in ppm



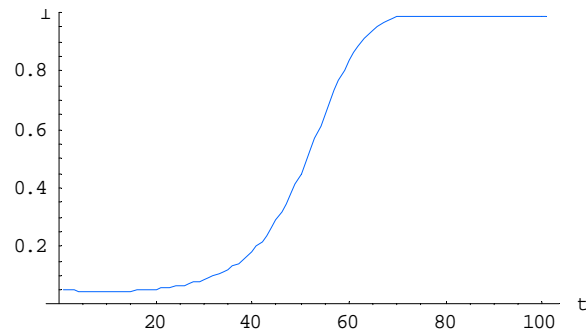
Temperature change in °C



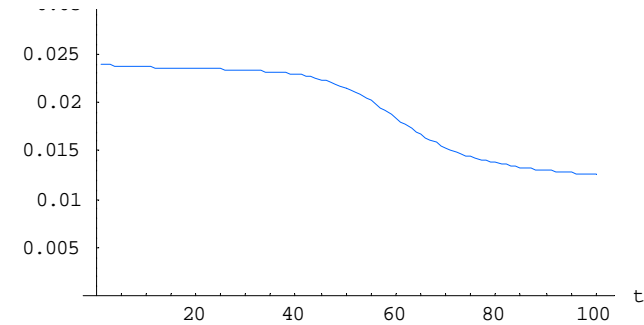
Climate damage/capita in \$10,000



Allocation to low-emission energy

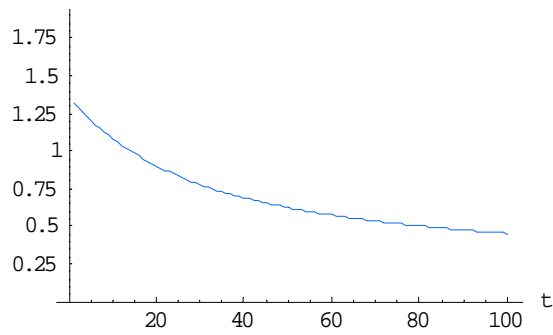


Carbon intensity of energy in GtC/EJ

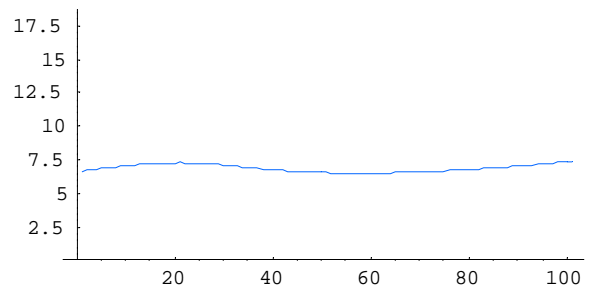


# Technical Change and Adaptive Control

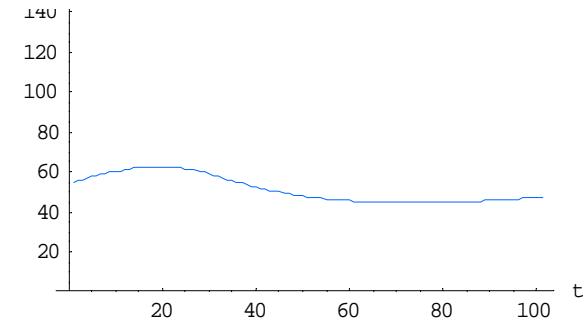
Emissions/capita in tC/cap



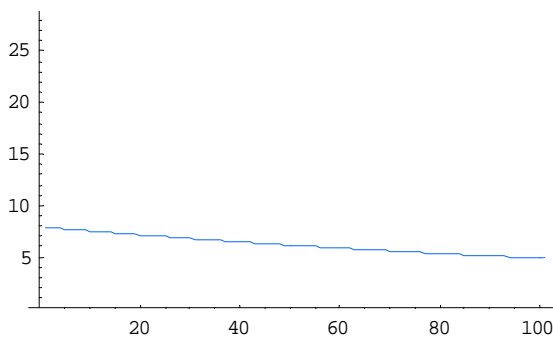
Production/capita in \$10,000



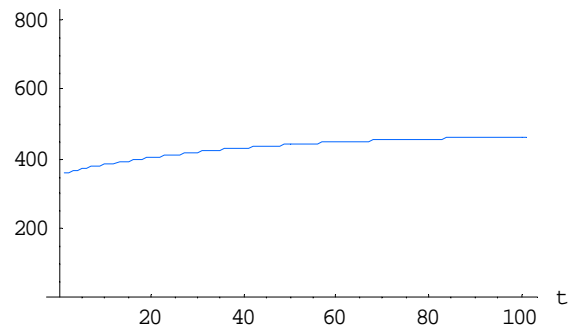
Energy/capita in GJ



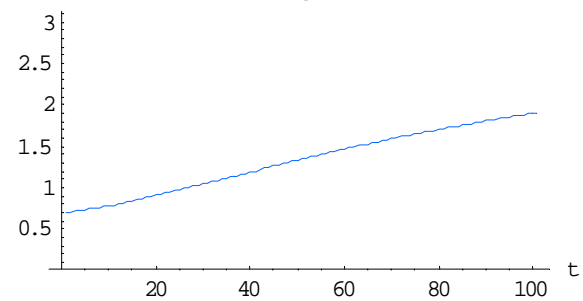
Emissions in GtC/a



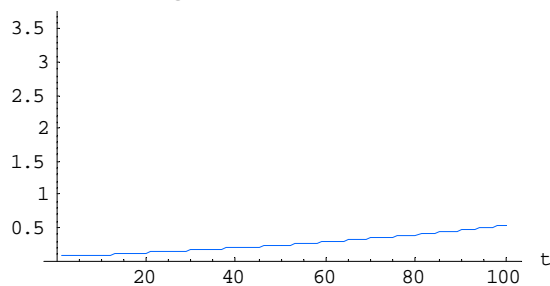
Atmospheric carbon in ppm



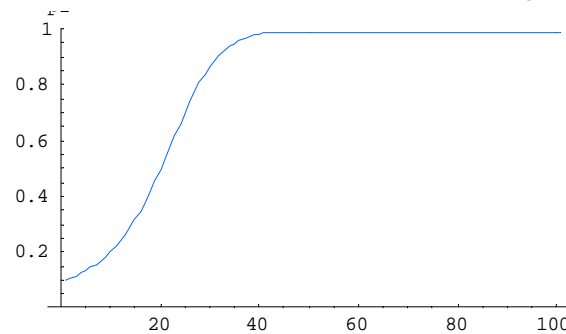
Temperature change in °C



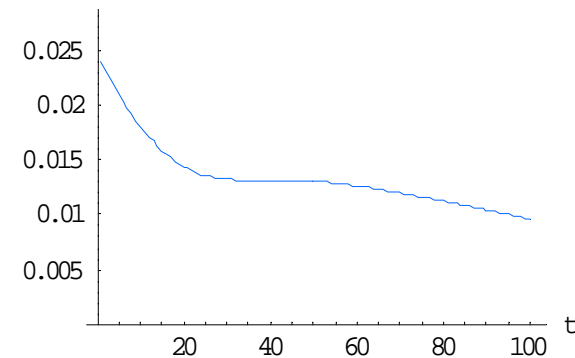
Climate damage/capita in \$10,000



Allocation to low-emission energy

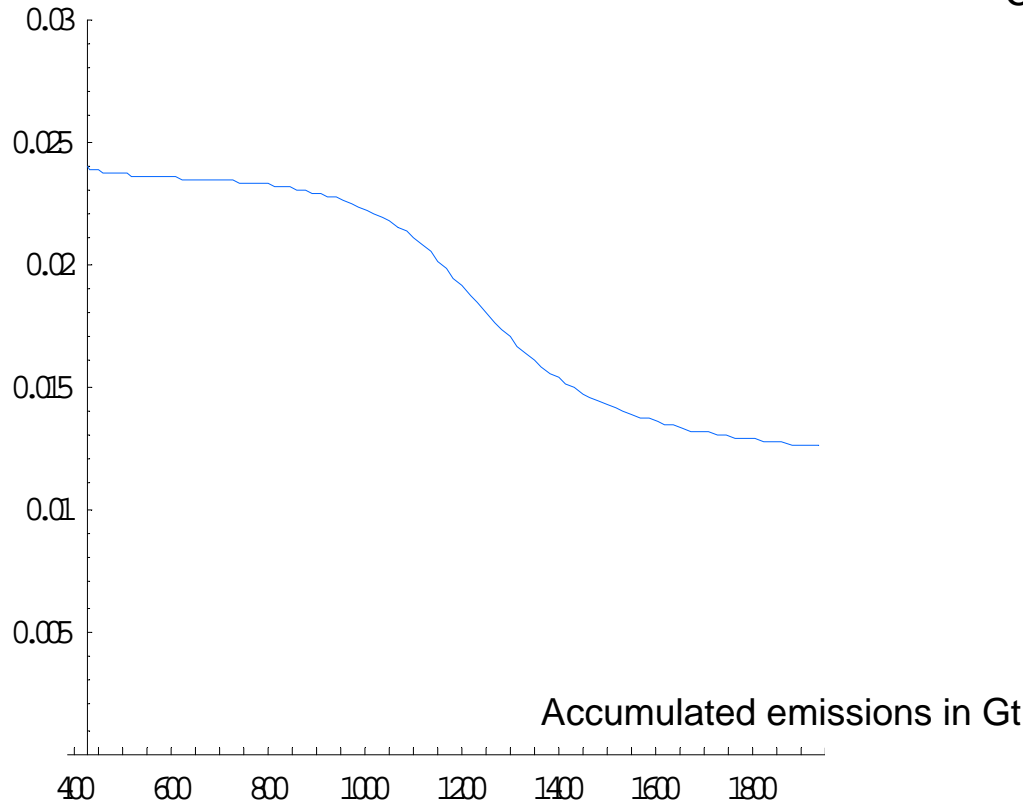


Carbon intensity of energy in GtC/EJ



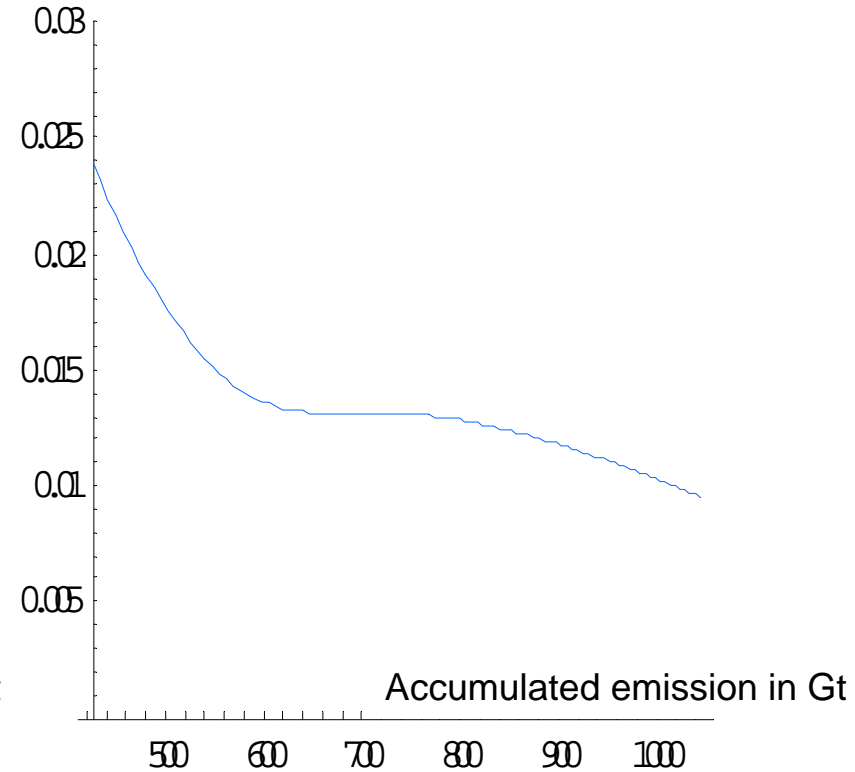
# Carbon Intensity vs. Accumulated Emissions

Carbon intensity of energy in GtC/EJ



Damage-induced control

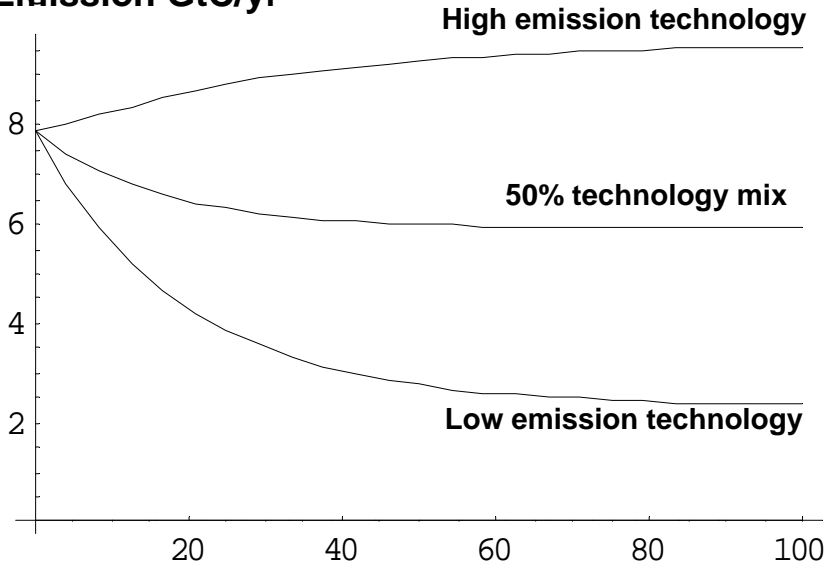
Carbon intensity of energy in GtC/EJ



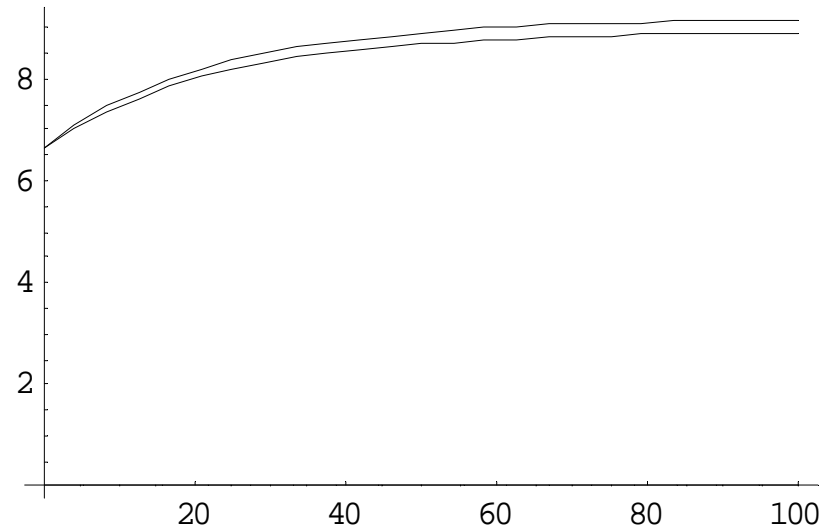
Adaptive targeting control

# Comparison of Technology Paths

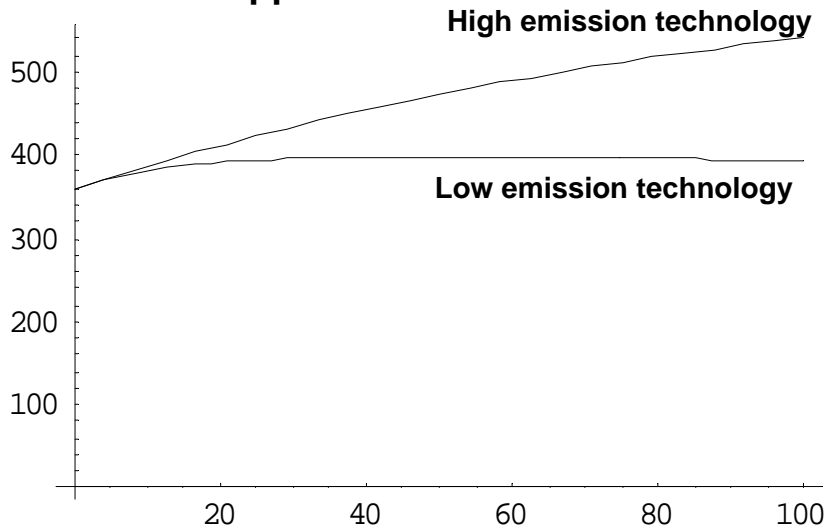
## Emission GtC/yr



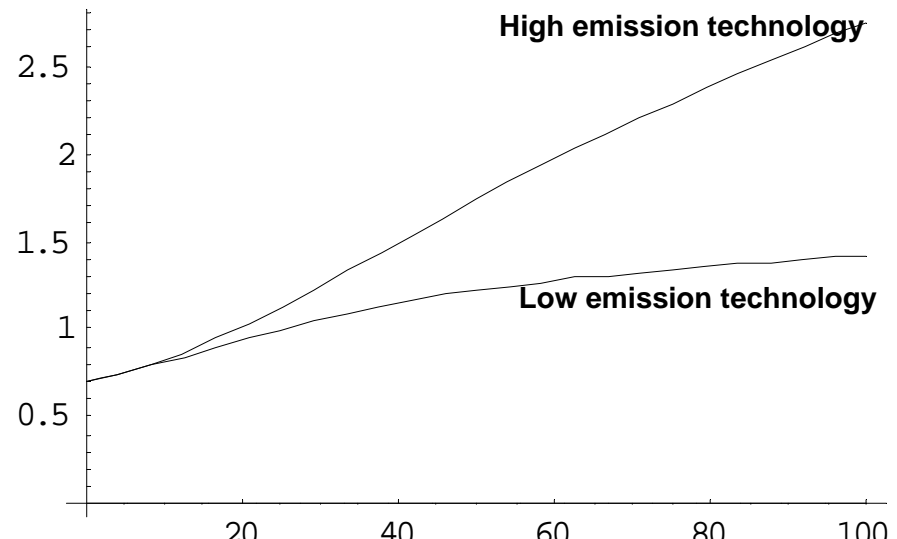
## Per capita production \$10000/yr



## Concentration ppm

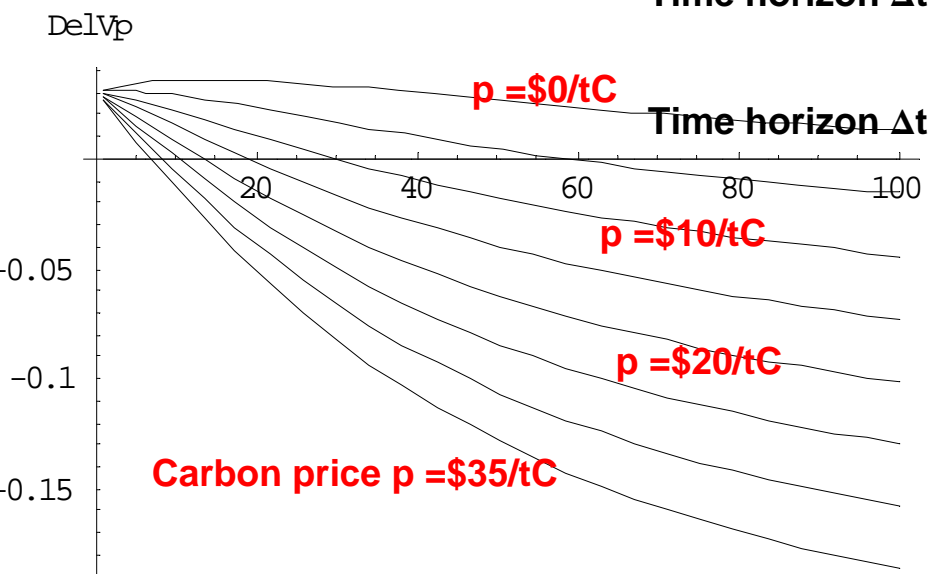
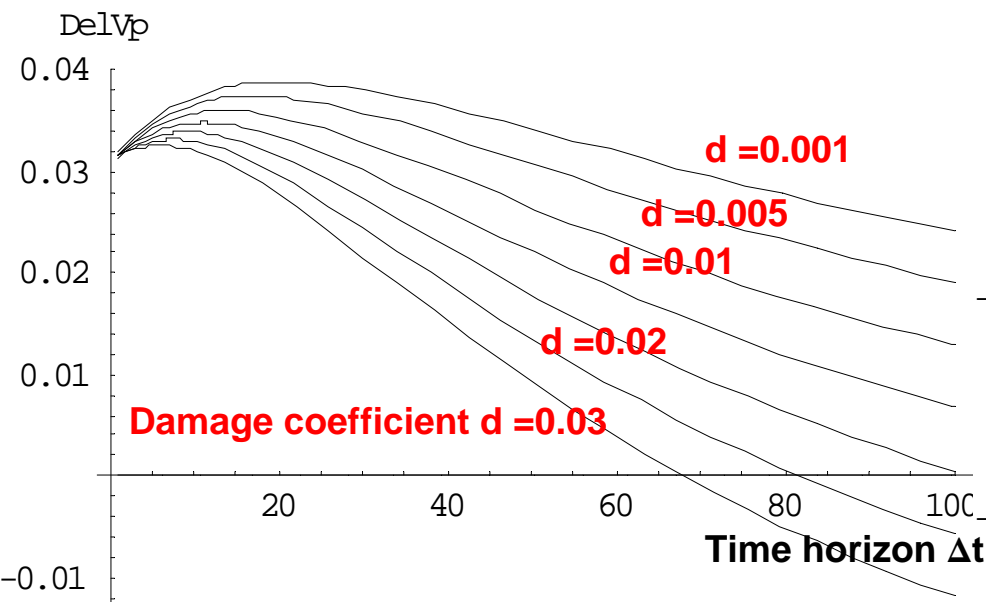
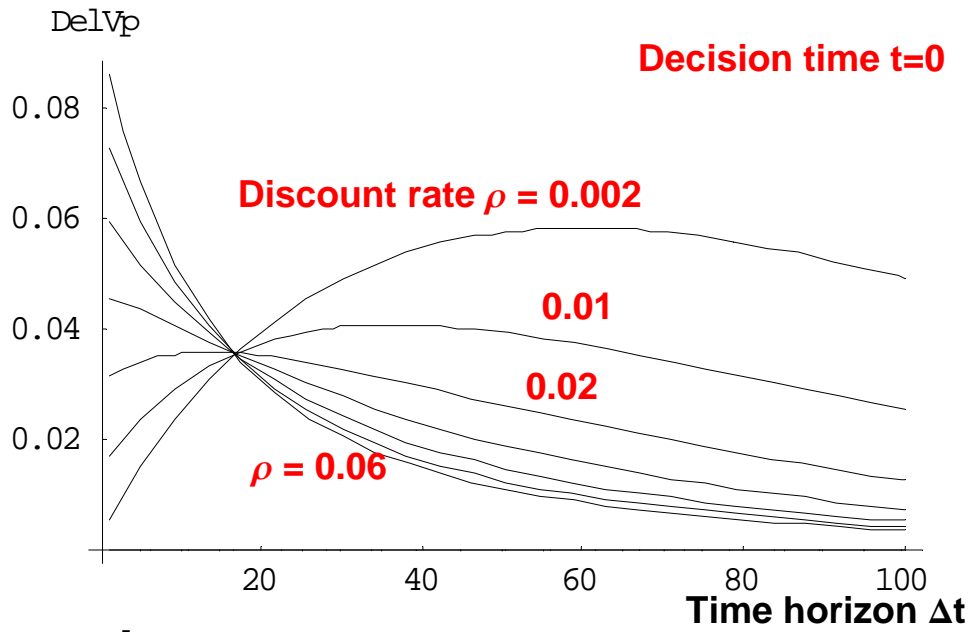
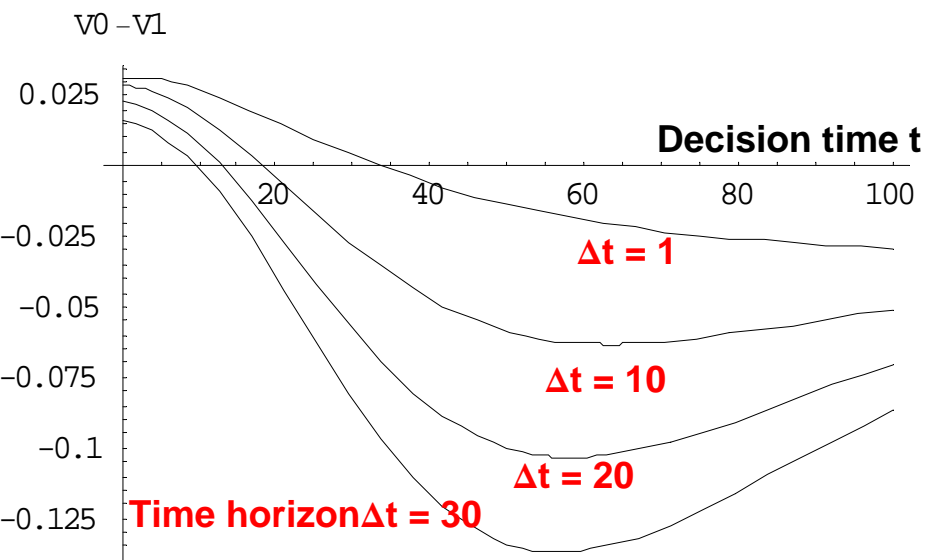


## Temperature change °C



# Value Difference High- vs Low-Emission Technology

## for Changing Time Horizon, Discount rate, Climate Damage and Carbon Price



# Emission Reduction: a Global Cooperation Problem

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$$G(t) = \sum_i G_i(t)(1 - r_i(t)) \leq G^*(t)$$

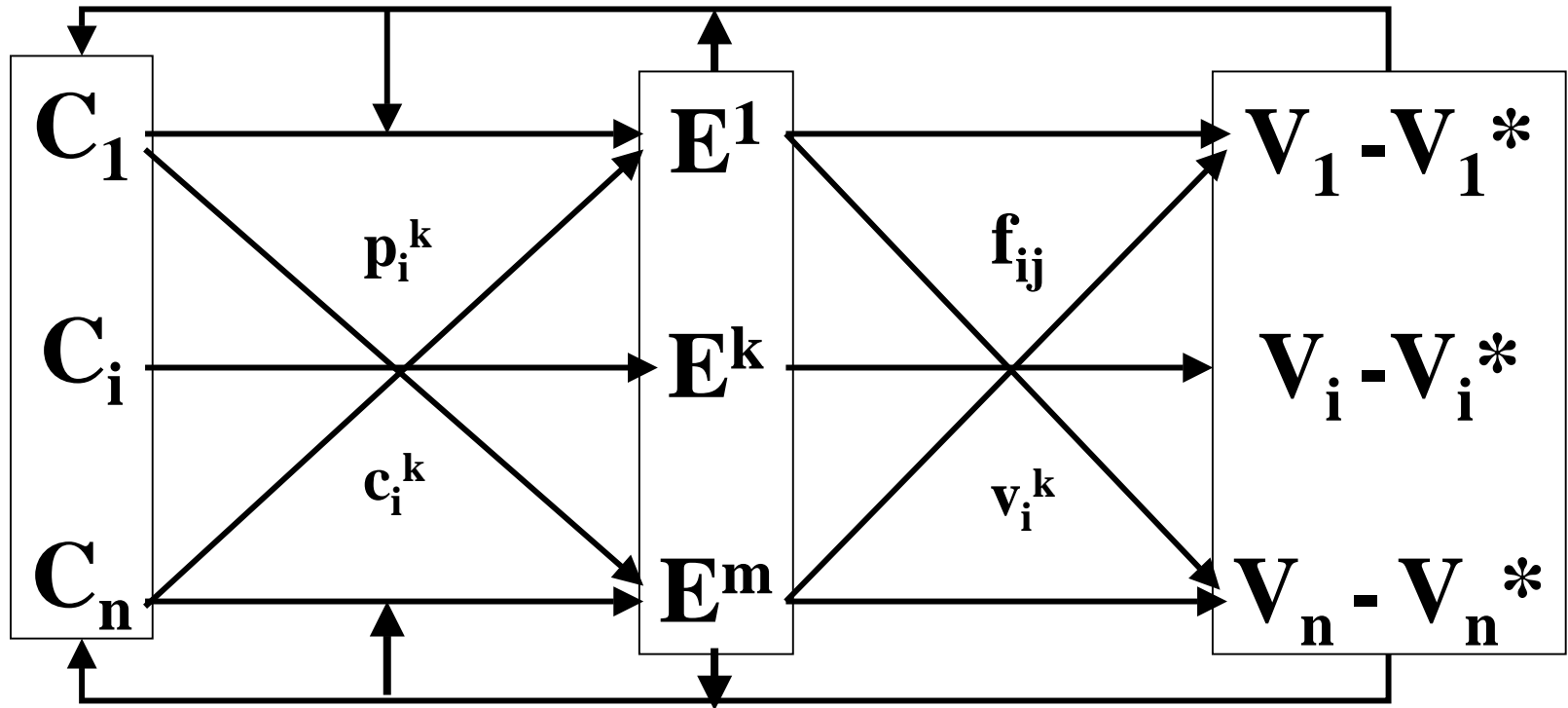
**$G(t)$ : Global emissions at time  $t$**

**$G^*(t)$ : Global emission target at time  $t$**

**$G_i(t)$ : Baseline emissions path of actor  $i$**

**$r_i(t)$ : Emission reduction of  $i$  from baseline**

# Integrated Assessment with Multiple Actors



Investment

Allocation  
Costs  
Prices

Energy  
Systems

Efficiency  
Benefits  
Risks

Values  
Goals

# Emission trading: multi-actor dynamics

Incremental value of firm for emission reduction  $r_i$

$$\frac{\partial V_i}{\partial r_i} = (-u_i + 2d_i G - 2c_i r_i \bar{G}_i + \pi) \bar{G}_i - \pi'_i (\bar{G}_i (1 - r_i) - G_i^*) \geq 0.$$

Emission trading price

$$\pi = \frac{\sum_i \pi_i^*}{n} = \frac{\sum_i u_i + 2c_i r_i \bar{G}_i - 2d_i G}{n}.$$

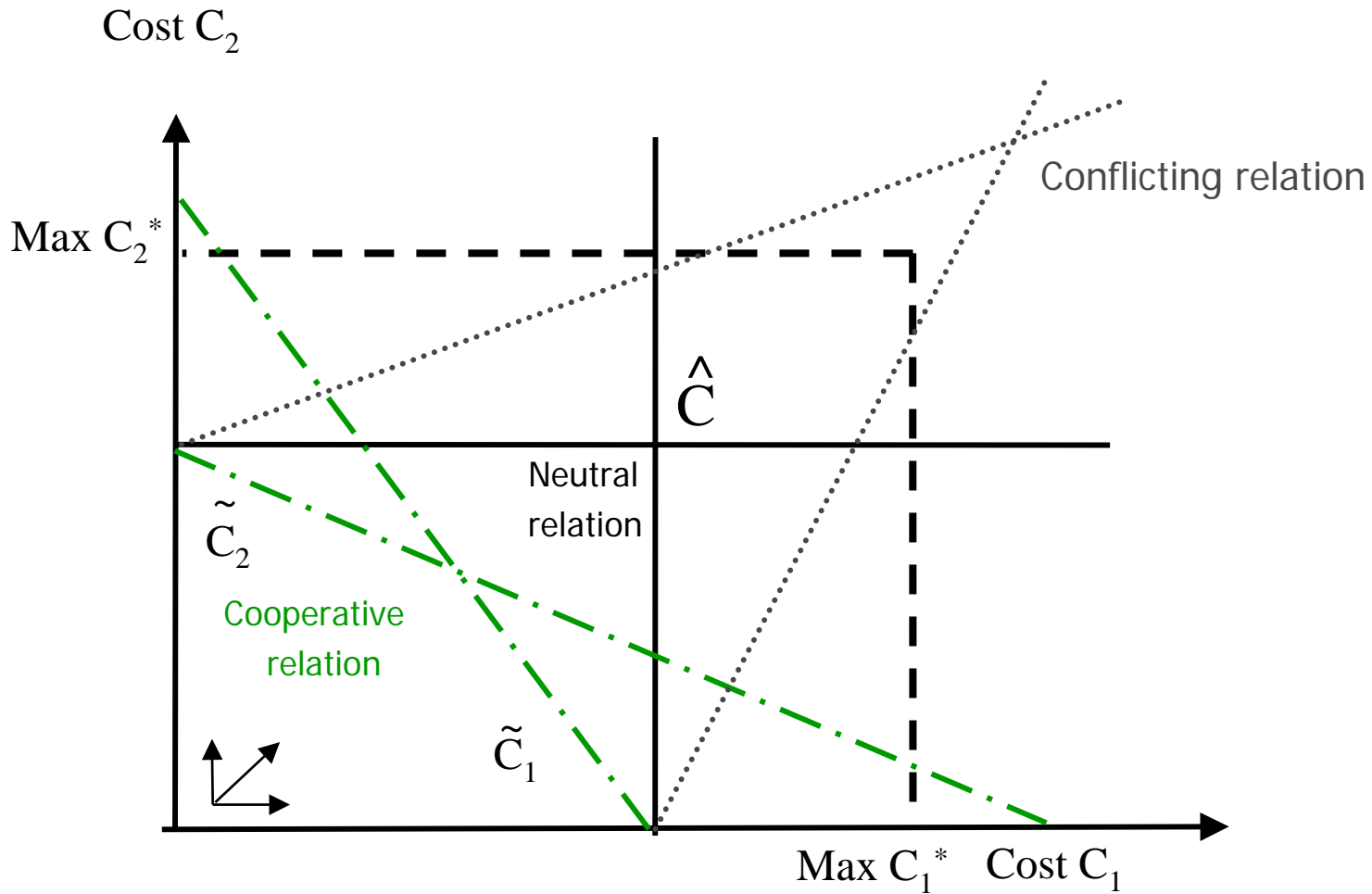
Optimal emission reduction

$$r_i^* = \frac{\sum_{j \neq i} \pi_j^* + u_i - 2d \bar{G}_i - n(u_i - 2d_i(\bar{G}_i + G_{-i})) + 2(G_i^* - \bar{G}_i)(c_i + d)}{2\bar{G}_i[(n-1)(d_i + c_i) - d_{-i}]}$$

$$\frac{\partial r_i^*}{\partial r_j} = \frac{2\bar{G}_j(c_j + d_{-i} - nd_i)}{2\bar{G}_i[(n-1)(d_i + c_i) - d_{-i}]}.$$

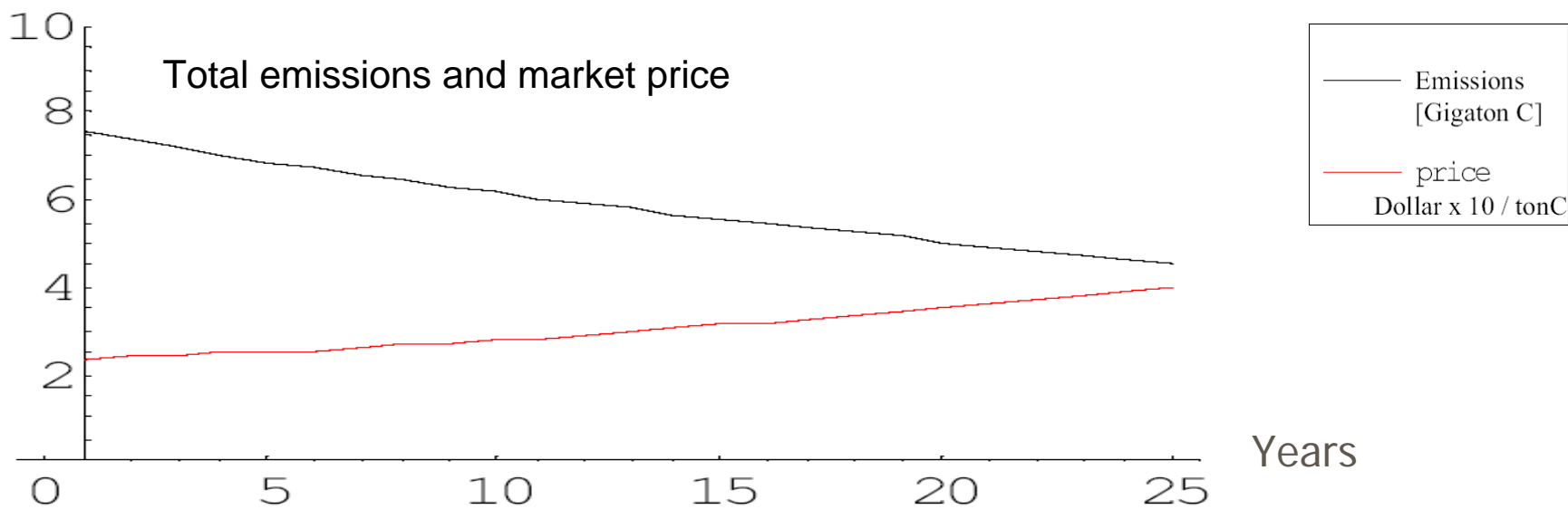
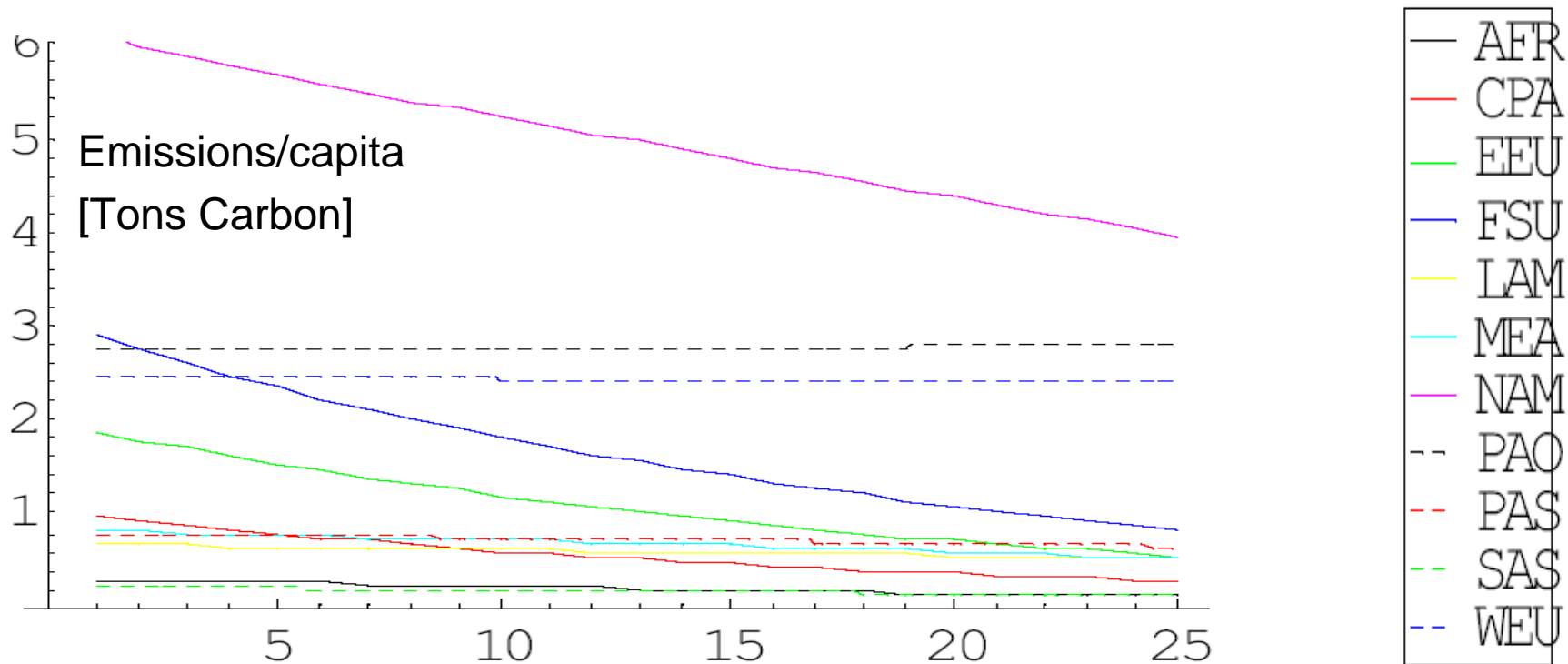
→ Coupled multi-player dynamics of emission reduction and permit price

# Conflict vs. cooperation



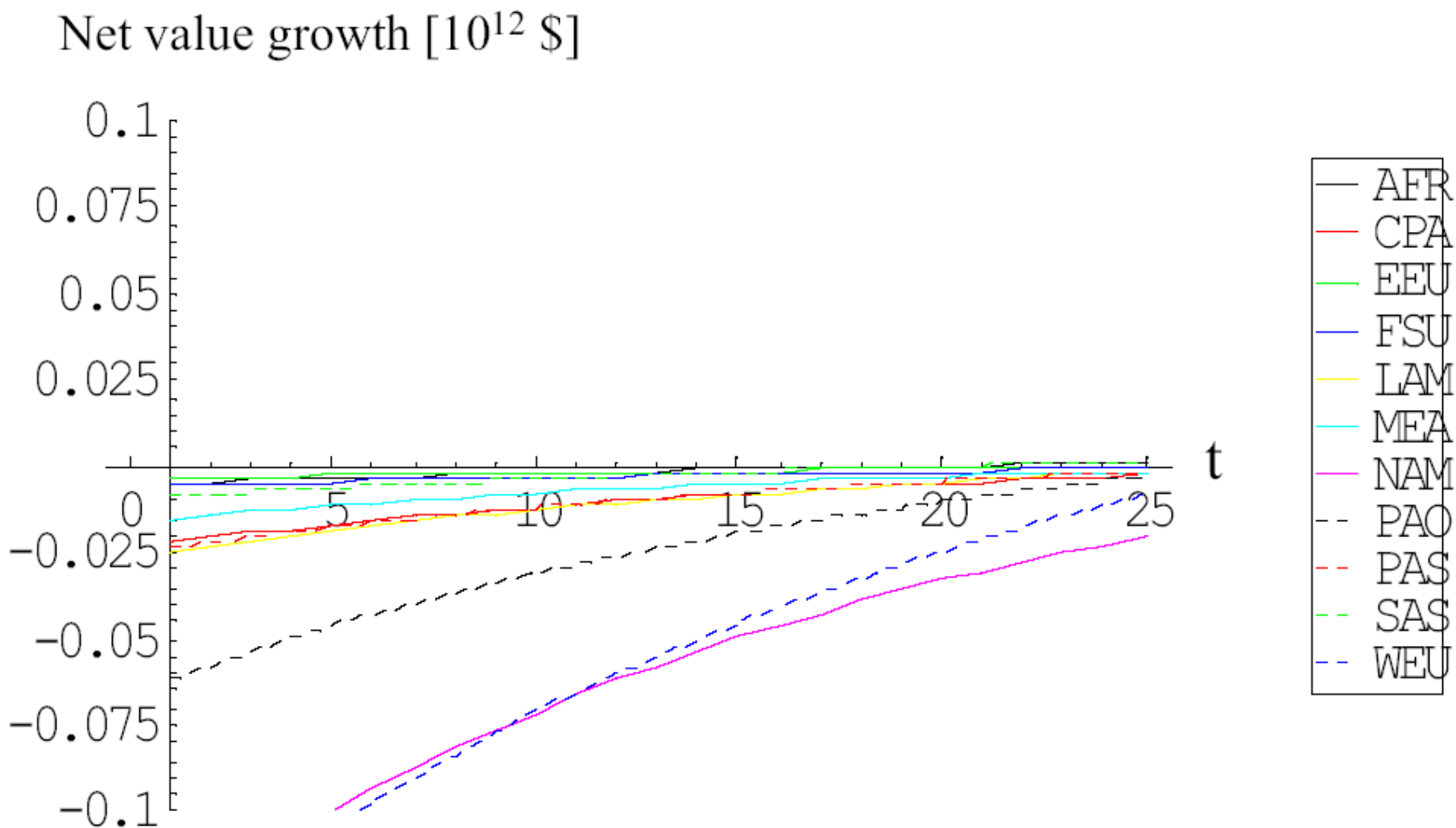
$$\text{Target cost } \tilde{C}_i = (\Delta V_i^* - f_{ij} C_j) / f_{ii}$$

# Simulation of Emission Tradings Among 11 World Regions

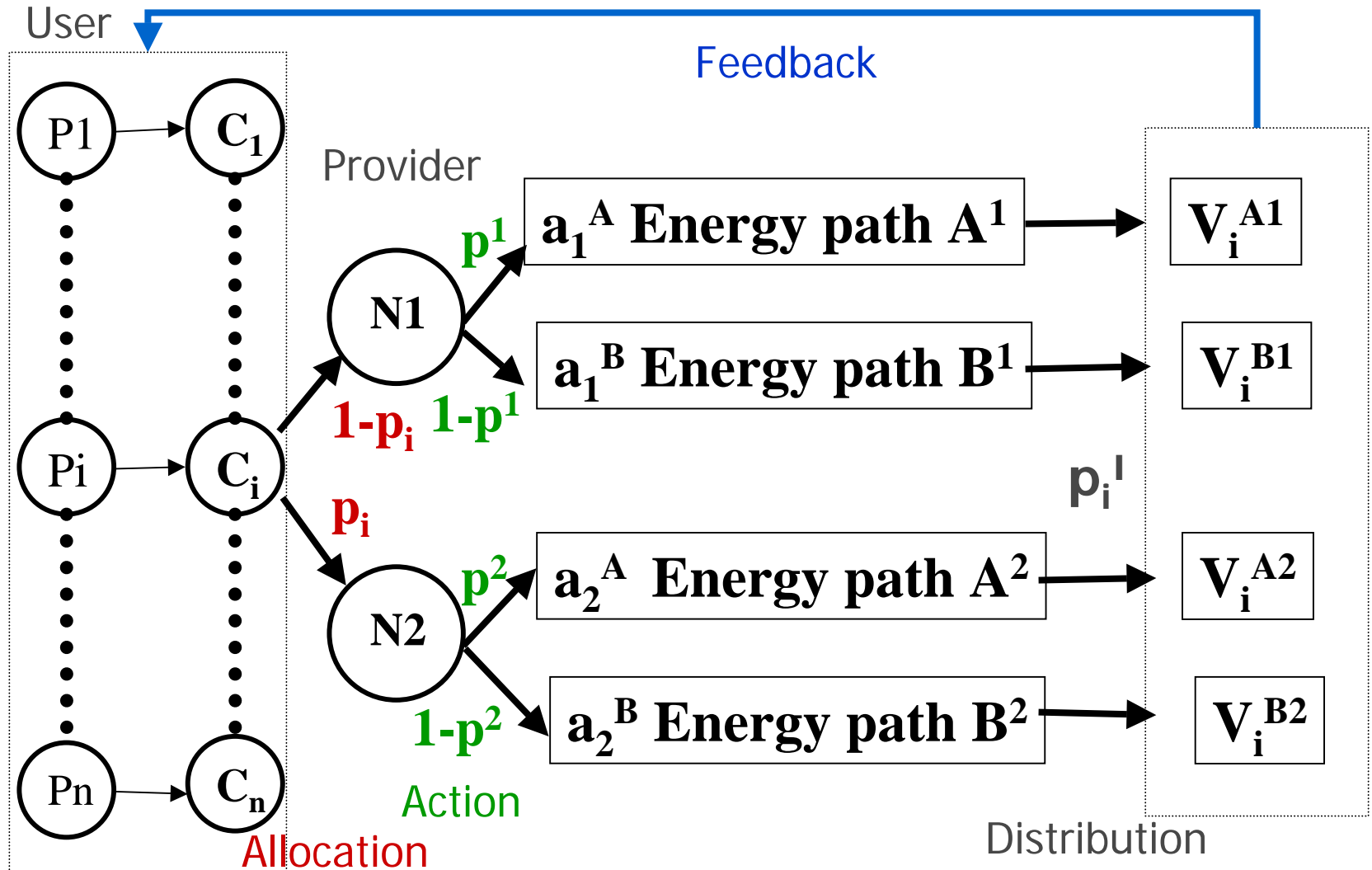


Years

# GDP losses from Emission Reductions

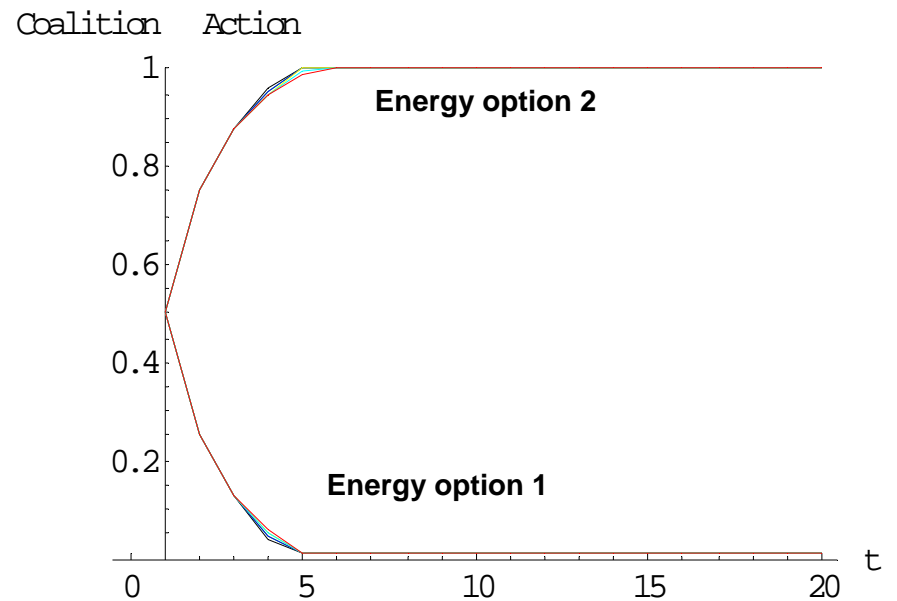
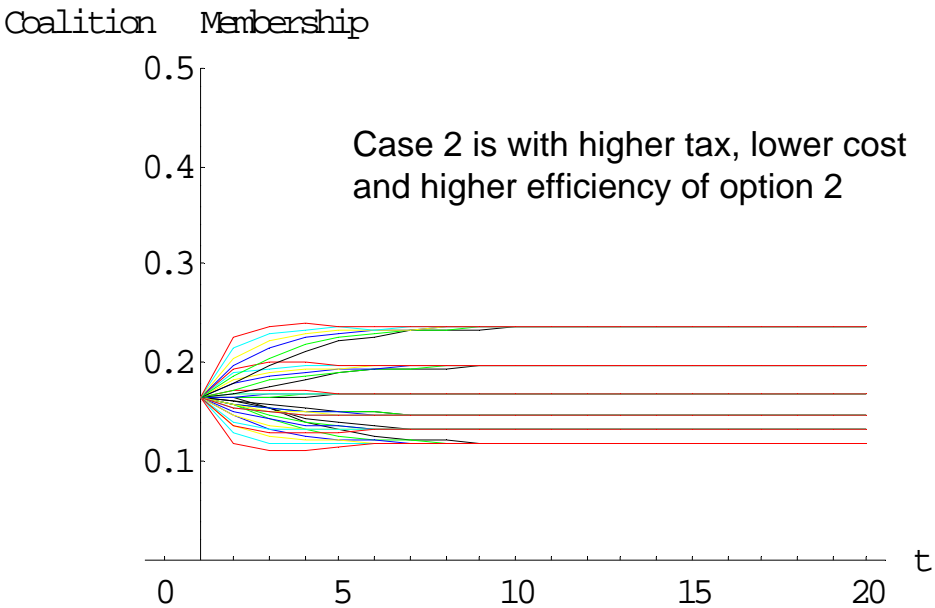
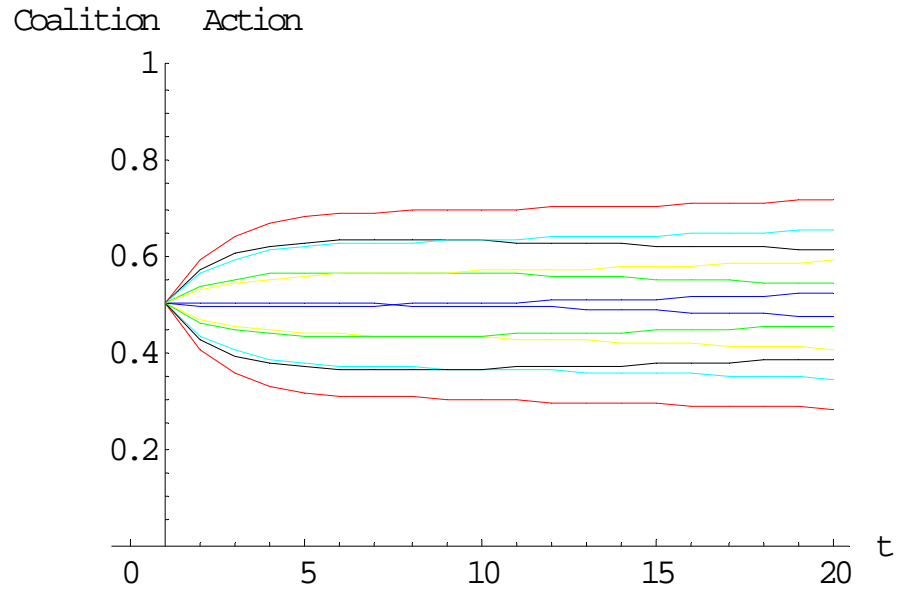
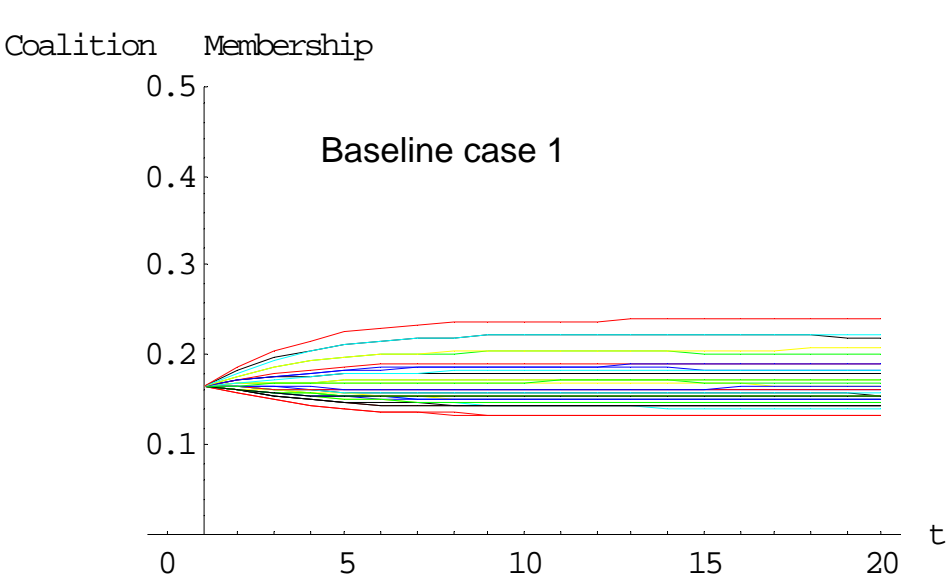


# Coalition Formation in Energy Use

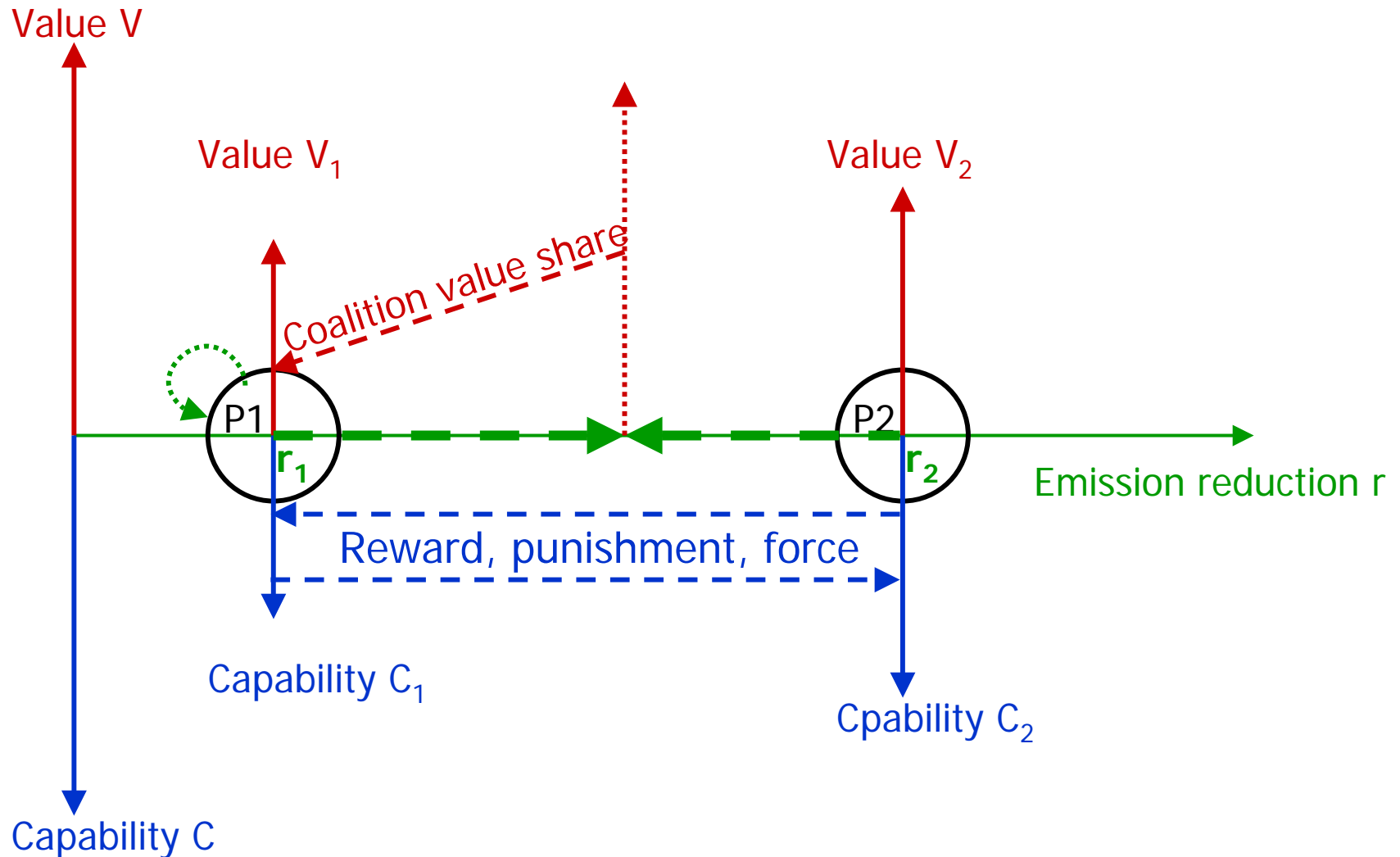


# Coalitions in Energy Management

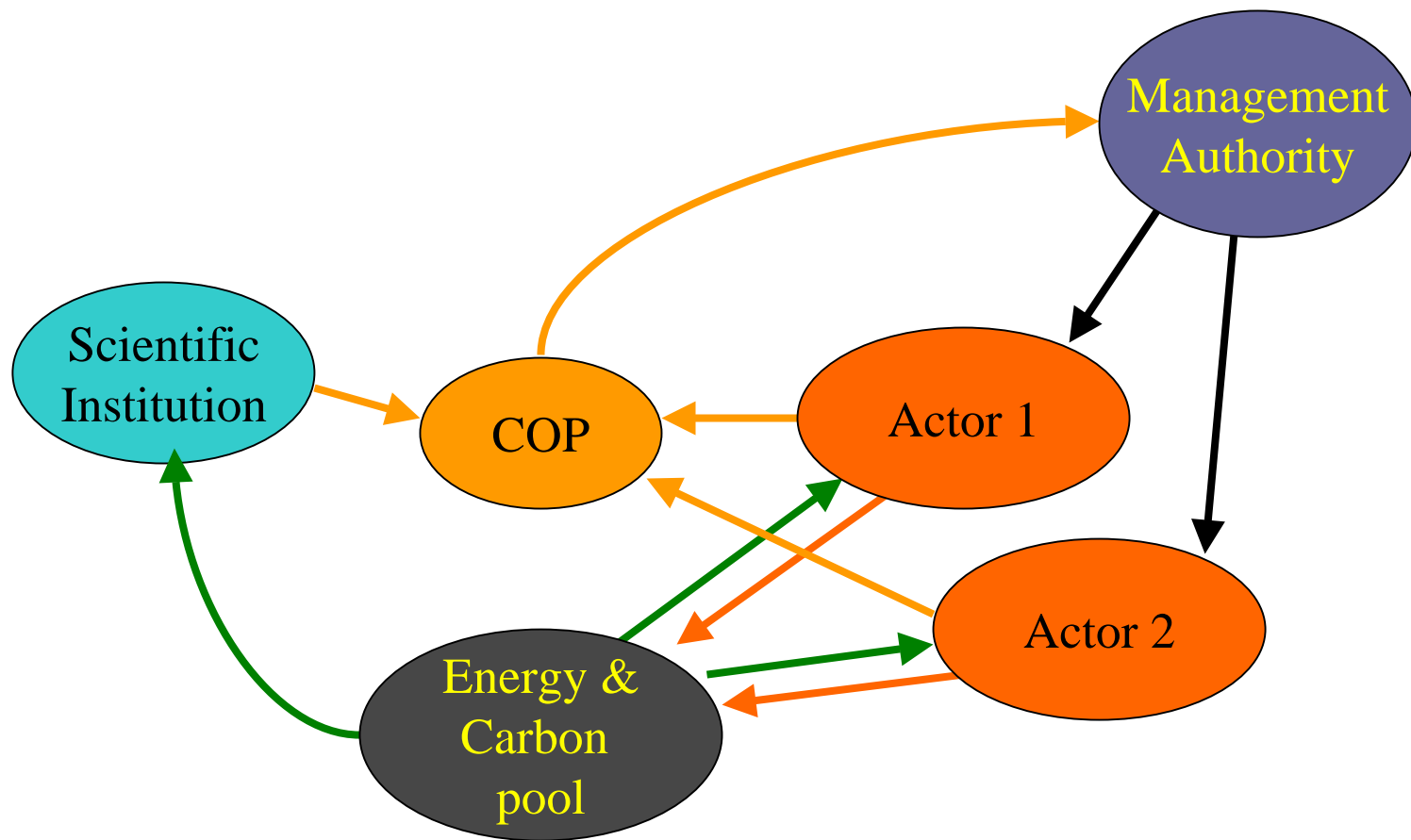
## Simulation with 6 users and 6 providers of energy

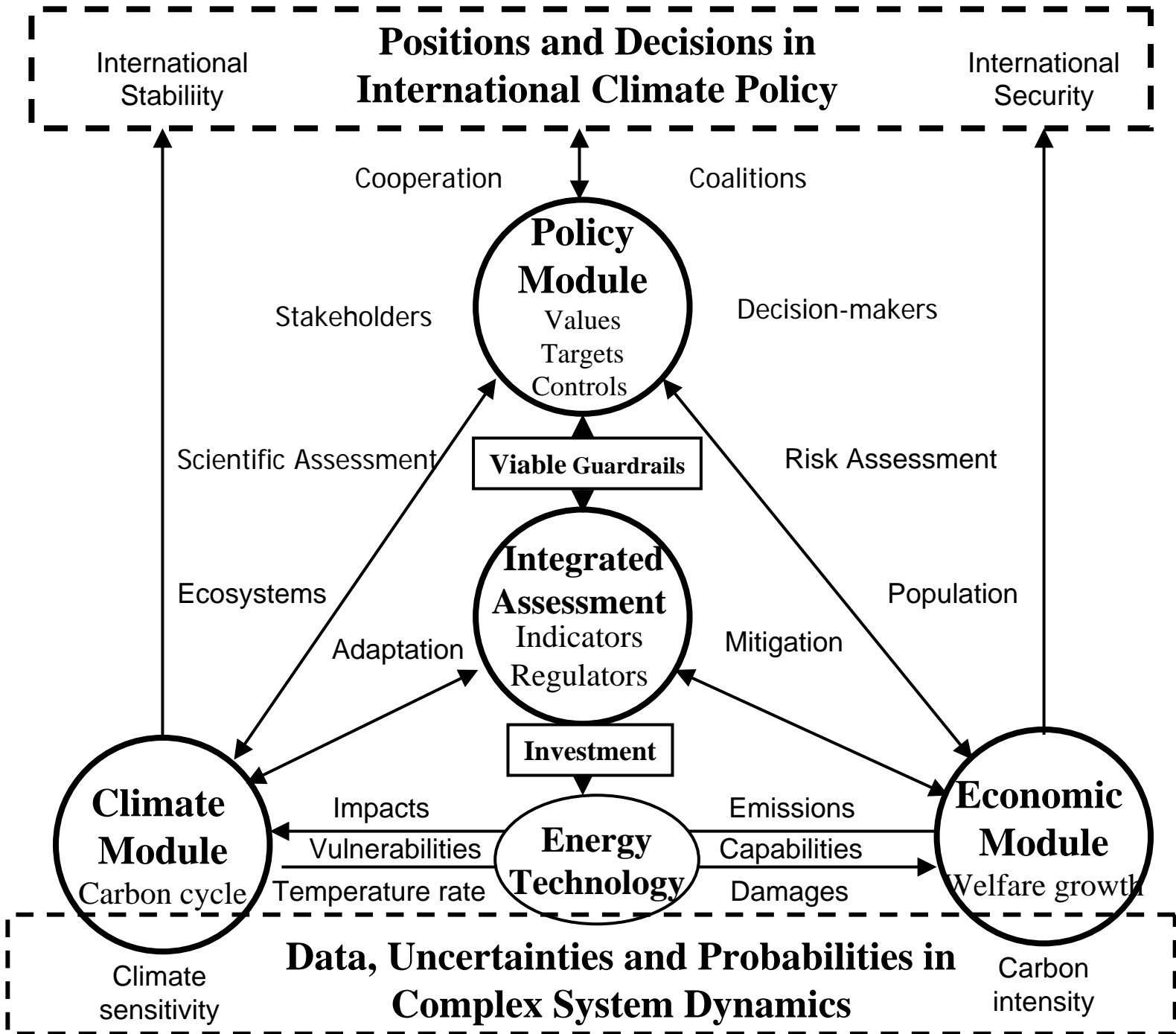


# Factors Influencing Position Change



# Cooperative Management of Energy and Climate Change





# Summary and Outlook

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- Analyse and compare specific energy technologies and paths with regard to economic and environmental conditions, including climate change and risk assessment
- Use advanced methods and modeling tools within integrated assessment framework
- Provide data-based modeling tools for adaptive control and decision-making under uncertainty
- Develop and integrate climate, economy and decisionmaking tools into a probabilistic integrated assessment framework on emission reductions and climate change
- Involve multi-actor interaction in understanding the chance of realization of policy actions.