Thank you

Engaging with policymakers: modelling of the optimal investments into environmental maintenance, abatement, and adaptation for long-term climate policies

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LONG-TERM STRATEGIES TO DEAL WITH CLIMATE CHANGE (IPCC, 2007)

- mitigation of greenhouse gas emissions
- adaptation to global warming

ADAPTATION to climate change - "*an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*" (IPCC,2007).

MITIGATION; ABATEMENT

mitigation - "*an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases*" (IPCC,2007).

Mitigation - a reduction in *net emissions* of greenhouse gases

Abatement - a reduction in *gross* emissions.

📖 IPCC (2007). Climate Change 2007, Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press

ADAPTATION

- covers investment in
  - diversification of crops, improvement in water resource management
  - a coastal protection infrastructure, implementation of warning systems
  - development of new insurance instruments, air cooling devices, etc.
- offers appealing & innovative technologies as a policy instrument
  - some are drawn by private agents' self-interest (air cooling in dwellings)
  - others have the property of a public good (*e.g*. dams)
- ∃ limits, barriers
  - environmental (barrier to migration)
  - economic (urbanization)
  - social (uneven across and within societies)
  - informational, attitudinal, financial, etc.

Policy issue about adaptation:

- estimation of right incentives to reach an optimal level of adaptation
- financial issues to address adequate adaptation measures:
  - ~75-100 bln USD/year- adapting to 2°C t↑ by 2050 (World Bank 2009)
  - ~ 28 - 67 billion USD / year - the av. cost of adaption in developing countries. Study for 2030 on five sectors (water supply, human health, coastal zones, forestry, fisheries) (UNFCCC, 2007).

People can protect themselves from adverse impacts of climate change but cannot avoid them (adaptation does not tackle the climate change causes) ⇒ the world cannot neglect abatement.

📖 UNFCCC (2007). Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries, United Nations Framework Convention on Climate Change.

📖 World Bank (2009). The Costs to Developing Countries of Adapting to Climate Change: New Methods and Estimates. The Global Report of the Economics of Adaptation to Climate Change Study, Consultation Draft.

MITIGATION; ABATEMENT

- quotas (on fossil fuel production)
- alternative energy sources (nuclear power, renewable energy)
- energy efficiency and conservation
- carbon sequestration
- reforestration and avoided deforestation
- geoengineering (an alternative to mitigation, mitigation)
- urban planning
- governmental and inter governmental actions (Kyoto-05, Copenhagen-09)
- non- governmental approaches

GOALS:

- Provide an analytic framework for modeling of the optimal long-term investment into the adaptation and abatement
- Find the optimal balance bw adaptation measures and emission abatement to implement an efficient long-term climate policy
- Investigate whether abatement and adaptation are substitutes or complementary policy instruments
- Find out whether the country's stage of development influences the optimal policy mix between mitigation and adaptation

Such research reflects a potential conflict of interests among countries and may have essential policy implications.

MODEL:

- a one country case
- the Solow-Swan one-sector macroeconomic growth framework
- a Cobb-Douglas technology with const returns to produce *final good* ***Y***
- the social planner assigns ***Y*** across the *consumption* ***C***, the *investment* I_K into the *physical capital* ***K***, the *investment* I_D into *environmental adaptation* ***D***, and the *emission abatement expenditures* ***B***:

$$Y(t) = AK^{\alpha}(t) = I_K(t) + I_D(t) + B(t) + C(t)$$

production eq. **distribution eq**

$A>0$ & $0<\alpha<1$ -parameters of the Cobb-Douglas PF

α- share of capital in production

A – the level of technology

A developing country: small productivity factor A+ high impatience degree ρ,

A developed country: a high global productivity A+ smaller impatience ρ.

The Law of motion of for the physical capital and the adaptation capital

$$K'(t) = I_K(t) - \delta_K K(t), \qquad K(0)=K_0,$$

$$D'(t) = I_D(t) - \delta_D D(t), \qquad D(0)=D_0,$$

$\delta_K \geq 0$, $\delta_D \geq 0$ - *deterioration coefficients* for physical capital and adaptation capital

$$I_K(t) \geq 0, \quad I_D(t) \geq 0, \quad C(t) \geq 0$$

Maximize the utility of the infinitely lived representative household:

$$\max_{I_K, I_D, C} \int_0^\infty e^{-\rho t} U[C(t), \underline{P(t)}, \underline{\underline{D(t)}}] dt = \max_{I_K, I_D, C} \int_0^\infty e^{-\rho t} (\ln C(t) - \eta(D(t)) \frac{P^{1+\mu}(t)}{1+\mu} dt$$

ρ>0 - the *rate of time preference* **$P(t)$**- the pollution intensity

$U(C,P,D)$ is additively separable (Gradus and Smulders, 1993; Stokey, 1998; Byrne, 1997; Hritonenko and Yatsenko, 1999; Economides and Philippopoulos, 2008; etc.)

$\eta(D)$>0-

- the *environmental vulnerability* of the economy to climate change;
- can be reduced by investing in adaptation $\Rightarrow \eta$ is the *efficiency of adaptation measures* to protect people and the environment from damages of climate change; $\eta \downarrow$ in D

μ>0 reflects the negative increasing marginal utility of pollution

***P*(*t*)**- the pollution, measures the environmental quality (e.g., the concentration of greenhouse gases in the atmosphere)

A law of motion for *P*: (Toman and Withagen, 2000; Jones and Manuelli, 2001. Stokey, 1998; Hritonenko and Yatsenko, 2005; Chen et al., 2009): The pollution is accumulated as a **stock**.

$$P'(t) = -\delta_P P(t) + \gamma Y(t)/B(t), \qquad P(0)=P_0$$

$\gamma>0$ - the *emission impact factor*; the "environmental *dirtiness*" of *Y*; the pollution intensity of the economy; net flow of pollution, e.g., the flow resulting from productive activity and abatement efforts; $P\uparrow$ as $\gamma\uparrow$

$\delta_P>0$- a const natural decay rate of the *P* stock deterioration, $P\uparrow$ as $\delta_P\downarrow$

MODEL / SUMMARY:

- a macroeconomic growth model with the environmental quality and specifications of production and pollution processes and social preferences
- a social planner problem with accumulation of a physical capital and a mix of adaptation and abatement investments
- the utility includes environmental impact and depends on the adaptation expense
- the economy uses the Cobb-Douglas PF to produce a final good
- the optimal policy mix with respect to the stage of development of the economy (country) and other issues

METHOD OF INVESTIGATION

benchmark with pollution abatement, η=const, D=0

- obtain the 1st order extremum conditions, decision variables I_K, C
- determine the interior optimal dynamics
- establish the stable steady–state equilibrium
- show that asymptotical convergence of the optimal trajectories $\{K,B,C,P\}$ to the steady-state
- provide a comparative static analysis
- investigate qualitative properties of model parameters and the relation between the optimal long-term abatement policy and model parameters

introduce a parameter

$$\kappa = \eta \left(\frac{\gamma}{\delta_P} \right)^{\mu+1} \frac{1-\alpha\delta/(\rho+\delta)}{1+\rho/\delta_P}$$

κ–indicator of environmental pressure,

- combines
  - the pressure γ/δ_P of the economy (human activity) on the environment (the pollution intensity γ of economic activity compared to the decay rate δ_P of the pollution stock)
  - the pressure η of the environment on welfare

choose a realistic *environmental vulnerability* $\eta(D)$:

$$\eta(D) = \underline{\eta} + (\overline{\eta} - \underline{\eta})e^{-aD}, \quad \overline{\eta} > \underline{\eta} > 0, \quad a > 0$$

- ↓ in D efforts from max $\eta(0)=\overline{\eta}>\underline{\eta}$ ($D=0$), to min $\eta(\infty)=\underline{\eta}>0$, ($D\to\infty$)

reflects the assumption of decreasing returns of D

the range of D opportunities; the benefits in terms of vulnerability reduction associated with D measures; depends on characteristics of the economy (altitude, importance of coastal areas, etc.)⇒the potential welfare gain between D=0 and full D can vary depending on the country

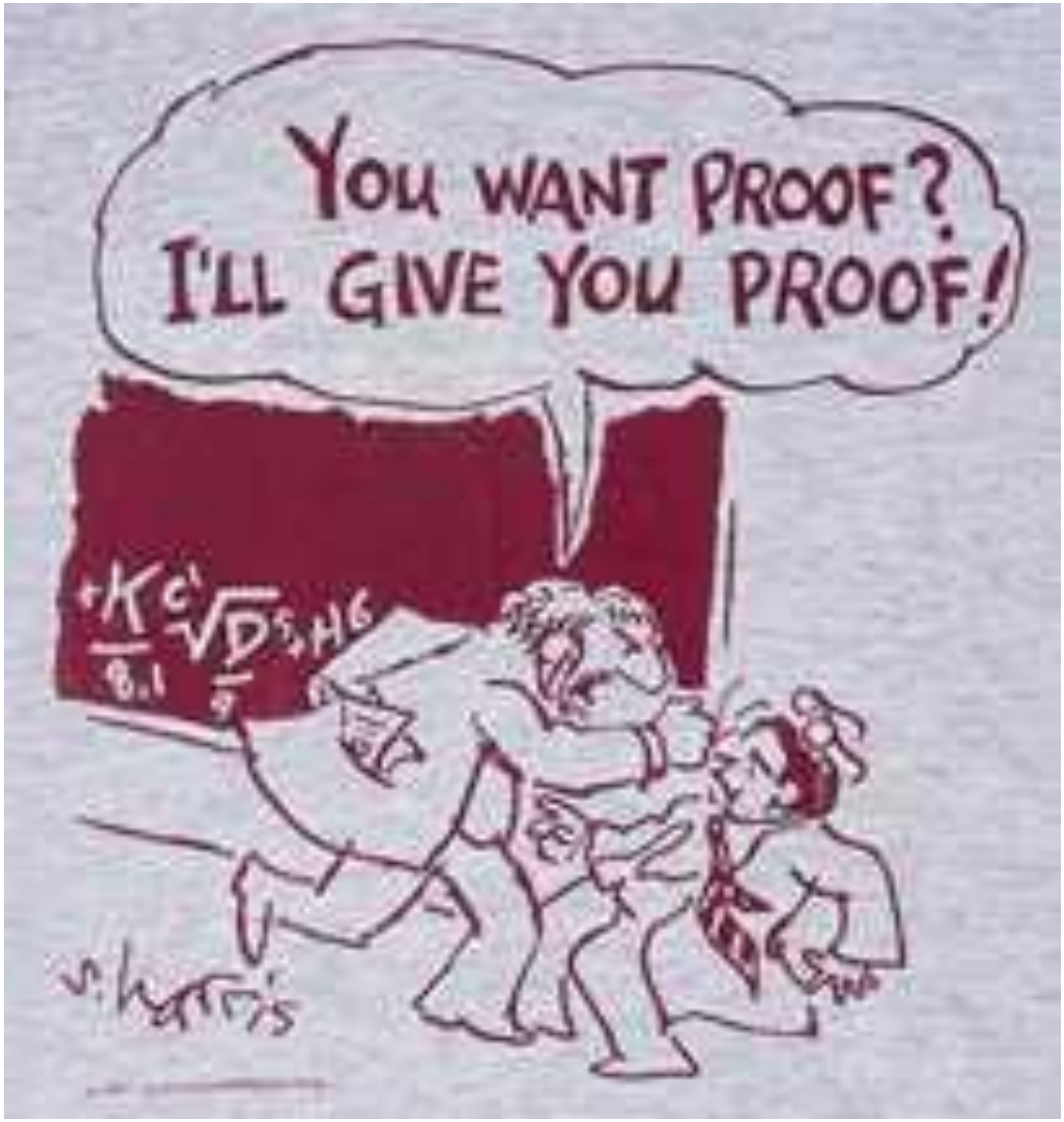
$M_\eta = a(\overline{\eta} - \underline{\eta})e^{-aD}$ - the *marginal efficiency* of adaptation;

higher first, then ↓ with the amount of investment (*e.g.*, dams significantly ↓ the environmental vulnerability of a country/region, the further decrease require larger investments).

analyze the impact of the adaptation

- obtain the first order extremum conditions
- determine the interior optimal dynamics
- establish the stable steady–state equilibrium
- show convergence of $\{K^*, B^*, C^*, P^*, D^*\}$ to the steady state
- provide comparative static analysis
- investigate qualitative properties of model parameters and relation bw the optimal long-term abatement and adaptation policy:
- $\exists \overline{K}_c$

$$D \begin{cases} = 0 & \overline{K} \le \overline{K}_c \\ > 0 & \overline{K} > \overline{K}_c \end{cases}$$ for $\overline{K} \in [0, \overline{K}_c]$ the optimal adaptation


YOU WANT PROOF?
I'LL GIVE YOU PROOF!
S. Harris

- ∃ the threshold value of the marginal adaptation efficiency M_η

$$D\begin{cases} = 0 & M_\eta \le M_{\eta cr} \\ > 0 & M_\eta > M_{\eta cr} \end{cases}$$

$$\mathrm{M}_{\eta cr} = \left[\left(\frac{\gamma}{\delta_P} \right)^{(\mu+1)\alpha} \frac{\rho\bar{\eta}(\mu+1)^{1-\alpha}}{A(1+\rho/\delta_P)\alpha^{\alpha}} \right]^{\frac{1}{1-\alpha}}$$

  - a developed country (A large, ρ small) will engage sooner in adaptation than a developing country (A small, ρ large).
  - the economy is productive ⇒ support adaptation of smaller efficiency; cost of adaptation < important than the environment quality
  - smaller pollution intensity γ ⇒ less efficient abatement activities ⇒ more room for the adaptation.

$$M_{\eta cr} = [a(\overline{\eta} - \underline{\eta})]_{cr} = \left[\left(\frac{\gamma}{\delta_P} \right)^{(\mu+1)\alpha} \frac{\rho \overline{\eta} (\mu+1)^{1-\alpha}}{A(1+\rho/\delta_P)\alpha^{\alpha}} \right]^{\frac{1}{1-\alpha}}$$

- small natural pollution depreciation δ_P; large pollution intensity $\gamma \Rightarrow M_{\eta cr} \uparrow \Rightarrow$ more to abatement
- the optimal policy mix bw spending on the economy in adaptation or in abatement depends on the nature of the pollutant ($\delta_P; \gamma$). The relative importance of environment-related investments $\uparrow$ with longer lived pollutant

- an *explicit* approximate solution under assumptions

$$\underline{\kappa} = \left(\frac{\gamma}{\delta_P}\right)^{\mu+1} \frac{\underline{\eta}}{(1+\rho/\delta_P)} >> 1$$

$$\left(\frac{A}{\rho} a^{1-\alpha}\right)^{1/\alpha} >> \underline{\kappa}$$

the economy has reached its min level of vulnerability; *κ–indicator of environmental pressure* is high; includes the min vulnerability $\underline{\eta}$ $\Rightarrow$ the economy cannot avoid the adverse effects of *P*, even when adaptation is implemented

the ratio of the global productivity *A* and the adaptation efficiency *a* to to the discount factor ρ

$$\overline{K} \cong \left[\frac{\alpha A(\rho + \delta_P)\delta_P{}^{\mu}}{\underline{\eta}\rho\gamma^{\mu+1}} \right]^{\frac{1}{1-\alpha}}$$

$$\overline{B} = A\overline{K}^{\alpha} - \overline{K}\rho / \alpha$$

$$\overline{D} \cong \frac{1}{a(1-\alpha)} \ln\left[\left(\frac{a(\overline{\eta} - \underline{\eta})}{\mu + 1} \right)^{1-\alpha} \frac{A(\rho + \delta_P)\alpha^{\alpha}}{\underline{\eta}\rho\gamma^{\alpha(\mu+1)}\delta_P{}^{1-\alpha(\mu+1)}} \right]$$

- adaptation enhances the flexibility of the economy and allows it to suffer less from a given level of pollution, a suitable level of adaptation is beneficial for the economy
- a country protects itself with adaptation $\Rightarrow$ the optimal abatement effort can be smaller; the pollution level can be larger
- abatement and adaptation are imperfect substitutes: a positive adaptation investment reduces emission abatement investment
- the interaction between adaptation and abatement policy instruments depends on the country characteristics (the inversed U-shaped dependence on the productivity A)

The optimal policy mix bw *D* and *B* (has policy implications):

(i) the optimal abatement effort $\overline{B}/\overline{K}$ *is independent of the productivity A* (under assumptions made)*;*

(ii) the optimal policy mix

$$\overline{D}/\overline{B} = \begin{cases} 0 & 0 < A < Ac \\ \uparrow & Ac < A < Acr \\ \downarrow & A > Acr \end{cases}$$

- the global productivity of the economy is weak $\Rightarrow$ optimal to focus on abatement and not on adaptation
- the adaptation opportunities are wide (large M_η , small $\underline{\eta}$) $\Rightarrow$ the critical value of the productivity A_c is smaller

the objective functions along the steady-state

$$W_{ND} = \frac{1}{\rho}\left[\ln \frac{K_{ND}\rho}{\alpha} - \bar{\eta}\frac{P_{ND}^{\mu+1}}{\mu+1}\right] \qquad W_D = \frac{1}{\rho}\left[\ln \frac{K_D\rho}{\alpha} - \frac{\alpha}{aK_D} - \underline{\eta}\frac{P_D^{\mu+1}}{\mu+1}\right]$$

the contribution of consumption to welfare

the impact of the pollution

the opportunity cost of adaptation

- ***α/a***: \$1 in *D* contributes positively to welfare with a marginal efficiency weight a ⇒ opportunity cost due to a lower capital accumulation
- the pollution impact on welfare is weighted
  - by the minimal vulnerability level $\underline{\eta}$ with adaptation
  - by the maximal vulnerability level $\bar{\eta}$ when no adaptation
- the pollution level is larger under adaptation

- the country can reach a very high protection level (very small $\underline{\eta}$)⇒ the positive effect of adaptation is to increase the consumption level.
- the adaptation is available and optimally used ⇒the resources that are not spent for the pollution abatement can be used for capital accumulation⇒ a higher consumption level in the long run.

$$W_{ND} = \frac{1}{\rho}\left[\ln\frac{K_{ND}\rho}{\alpha} - \bar{\eta}\frac{P_{ND}{}^{\mu+1}}{\mu+1}\right] \qquad W_{D} = \frac{1}{\rho}\left[\ln\frac{K_{D}\rho}{\alpha} - \frac{\alpha}{aK_{D}} - \underline{\eta}\frac{P_{D}{}^{\mu+1}}{\mu+1}\right]$$

RESULTS

- an economic-environmental growth model with abatement & adaption; analysis uses comparative static analysis and perturbation techniques

- the existence of a unique steady state and convergence of the solution to the steady state

- analytical expressions for the optimal policy mix between emission abatement and environmental adaptation at a macroeconomic level

- the optimal policy mix between abatement and adaption investments D/B depends on the country economic potential: its dependence on economic efficiency has an inverted U-shape $\Rightarrow$ essential implications for associated long-term environmental policies.

- the economic efficiency is weak (poor country) $\Rightarrow$ no adaptation
- a high developed country $\Rightarrow$ reasonably small adaptation
- medium-developed countries $\Rightarrow$ larger adaptation efforts (in terms of D/B). Challenge Buod and Stephan (2010) : high income countries should invest in both mitigation and adaptation, while low income countries should invest only in mitigation

- Data calibration and numerical simulation of the optimal policies to illustrate theoretical outcomes

FURTHER ANALYSIS

- extend the model to an n-country model with strategic behaviors to study other cornerstones for the climate change problem ⇒ investigation of the Nash equilibrium and cooperative solutions in the case of two and n countries and discussion of differences between corresponding policies; Our model holds for a closed economy (the absence of external trade, a closed interaction between the economy and the environment, e.g., the environment is not a public good

- add technological change: results can alter & be more optimistic

MODELING OF FOREST CARBON SEQUESTRATION MANAGEMENT & IMPACT OF CLIMATE CHANGE

Goals:

1. Construct a mathematical model for rational forest management with impacts of climate change, benefits from carbon sequestration, mitigation costs

2. Implement dynamics of climate change from global scenarios

A: without climate changes

A2: a heterogeneous world: The population ↑, the economic development is regionally oriented, per capita economic growth and TC are slow

B2: a world with local solutions to economic, environmental sustainability

3. Derive the maximum principle & find bang-bang regime

4. Find the dependence of l_{max} on climate change scenarios

5. Investigate the growth dynamics of l under different scenario.

6. Find optimal management of carbon sequestration and timber production adapted to climate changes

7. Determine optimal carbon price within climate changes and impact on l_{max}

$$\int_0^T e^{-rt}\left\{\int_{l_0}^{l_m} B(x(t,l),u(t,l))dl + \rho_2(t)\left[\frac{db(t)}{dt}+\frac{ds(t)}{dt}\right]-\rho_3(t)p(t)\right\}dt \xrightarrow[x,u,p,\ b,s,E,\ V,W]{} \max$$

net benefits =timber production + carbon sequestration - expenses planting tree

$$\frac{\partial x(t,l)}{\partial t}+\frac{\partial[g(E(t),l)x(t,l)]}{\partial l} = -\mu(E(t),l)x(t,l)-u(t,l)x(t,l), \qquad \frac{ds(t)}{dt}=h\left(\frac{dV(t)}{dt},s(t)\right),\ s(0)=s_0$$

size-structured version of Gurtin-MacCamy model for managed forest-no bio reproduction

$$V(t)=\gamma_0\int_{l_0}^{l_m} l^\beta x(t,l)dl,\quad W(t)=\frac{dV(t)}{dt},\quad E(t)=\chi\int_{l_0}^{l_m} l^2 x(t,l)dl,\quad b(t)=\gamma_0\int_{l_0}^{l_m} v(l)l^\beta x(t,l)dl,\ v'(l)>0,$$

the dynamics of the carbon content in the forest ecosystem

$x(0,l)=x_0(l),\ l\in[l_0,\ l_m],\ g(t,l_0)\ x(t,l_0) = p(t),\ \ 0\le u(t,l)\le u_{\max}(t,l),\ \ 0\le p(t)\le p_{\max}(t),$

l - the diameter of a tree, ***x(t,l)*** - the distribution density of trees,
u(t,l) - the flux of logged trees, ***p(t)*** - the flux of new trees planted at t with l_0,
g(E(t),l) - the growth rate of trees, ***μ(E(t),l)*** - the instantaneous mortality rate,
E(t) - the forest density, ***V(t)*** - the above-ground volume of the forest biomass,
b(t), s(t) - the amount of carbon sequestered in the timber and soil,
$\chi, \beta, \gamma_0 > 0$ – empirical parameters of tree species

1. R.Goetz, N.Hritonenko, A.Xabadia, Y.Yatsenko, Using the Escalator Boxcar Train to determine the optimal management of a size-distributed forest when carbon sequestration is taken into account, in *Lecture Notes in Computer Science* 4818, Springer, Berlin, 2008, 334-341

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