# ME2708 Economic Growth

## Lecture 9: Natural Resources and Growth

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# Outline

# Introduction I

- Population has played a key (*yet different*) role in all economic growth models covered in this course
  - Exogenous growth and first-generation models of endogenous growth
  - Endogenous technological progress models
- Malthus' prediction that, because of rising population, the world economy was deemed to experience declining living standards has not been supported by data
  - **Data**: positive association between population or population growth and per capita incomes
  - **Theory**: population as the key driver of technological progress (endogenous growth models)

# Introduction II

- Malthusian arguments were re-introduced in the late 1960s and early 1970s in connection to natural resources:
  - Ehrlich's (1968) *The Population Bomb*
  - Meadows et al. (1972) *The Limits to Growth*
- Line of reasoning: too many people consume too many natural resources and create too much pollution, giving rise to natural disasters that ultimately lead to starvation
- Meadows et al.'s (1972) paper, highly controversial: if growth does not come to a halt, there will be fatal environmental consequences
  - Starting point for growth analysis taking nature into account

# Introduction III

- Most of the subsequent literature discussed how to achieve long-run growth in resource-limited environments
  - Pioneering paper: Nordhaus (1973)
  - Hotelling's (1931) rule enjoys a central role in this area of research:

    *For a non-renewable, exhaustible resource with completely known stock, no discoveries possible, no alternatives, no recycling, private ownership and constant costs of extraction, the price of the resource will increase at the interest rate over time*

- Other debated areas address:
  - Intergenerational welfare, i.e. the question of whether to pay less now or more later
  - Importance of regulatory measures (carbon taxes, R&D subsidies, etc.)
    - ⋆ carbon leakages, international agreements
  - Policy approach: immediate vs. gradual, stringency, etc.

# Introduction IV

- In this lecture we:
  - incorporate the finiteness of natural resources into the basic Solow framework
  - analyze equilibrium in this economy and its behavior along a *BGP*
  - quantify the importance of natural resources
  - look into the potential advantages of efficient pricing
  - discuss the relationship between growth and environmental quality
  - look at some empirical evidence
  - discuss *DTC in Energy Production* (Lööf and Perez, 2017)
  - summarize what we have done and (hopefully) learn in this course
  - clarify some issues *wrt* the written exam

# Natural Resources and Growth I

- Production function can be adapted to incorporate nonrenewable resources

$$Y(t) = F[A(t), E(t), K(t), L(t)]$$

  where variables are defined according to our standard notation and $E$ represents the energy input used in production

- Assuming production takes the Cobb-Douglas form,

$$Y(t) = A(t)E(t)^{\gamma}K(t)^{\alpha}L(t)^{1-\alpha-\gamma} \tag{1}$$

  where $\gamma$ and $\alpha$ represent the income share of nonrenewables and capital, respectively. Restrictions: $0 < \gamma < 1$ and $\alpha + \gamma < 1$

- One can then show that this production function exhibits CRS in capital, energy and labor taken together (*left as an exercise*!)

# Natural Resources and Growth II

- We keep the assumptions of the basic Solow framework:

$$\dot{A}(t) = A(t)g_A, \qquad g_A > 0 \tag{2}$$

$$\dot{L}(t) = L(t)n, \qquad n > 0 \tag{3}$$

$$\dot{K}(t) = sY(t) - \delta K(t) \tag{4}$$

  where $s, \delta \in (0,1)$ are the savings and depreciation rate, respectively

- We need to specify a law of motion related to the remaining input, $E$. We do so by combining facts with assumptions:
  - Nonrenewable resources are finite and depleted when used
  - Energy input, $E(t)$, comes from some *initial* nonrenewables base, $R(0)$
  - In period 1, after the economy has used $E$ nonrenewables, the remaining resource base is $R(1) = R(0) - E(0)$
  - So that the law of motion for $R$ is given by the differential equation,

$$\dot{R}(t) = -E(t) \tag{5}$$

# Natural Resources and Growth III

- What factors determine the amount of energy used in production, $E$, each period $t$?
  - GE problem (*beyond the scope of this course*)
  - (long-run) solution to this problem: *constant* fraction of the remaining stock of energy is used each period

$$s_E = \frac{E(t)}{R(t)}, \qquad 0 < s_E < 1$$

  - If $R$ depletes over time, $E$ must fall over time if constancy of $s_E$ is to be ensured!

- Dividing both sides of eq. (5) by $R$ we get,

$$\frac{\dot{R}(t)}{R(t)} = -s_E \tag{6}$$

i.e., the stock of nonrenewables declines at rate $s_E$

# Natural Resources and Growth IV

- The solution to the differential equation capturing the behavior of $R$ is similar to its technology counterpart in Solow

$$R(t) = R(0)e^{-s_E t} \tag{7}$$

but instead of exponential growth, we have exponential decay!

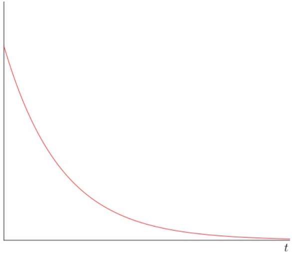



Figure: Nonrenewables stock over time

# Natural Resources and Growth V

- Solving for the energy input used in production each period, $E$,

$$\begin{aligned} E(t) &= s_E R(t) \\ &= s_E R(0) e^{-s_E t} \end{aligned} \tag{8}$$

- Important to note that $s_E$ is featured twice in the expression of $E$:
  (1) **positively**: the higher the fraction of the nonrenewables stock put in production, the more that can be produced in any given period

  (2) **negatively**: the higher the fraction of the nonrenewables stock used in production, the faster the resource base is depleted and the less energy is available for production in future periods

  (OE) starting at some $t > t^*$, the higher the fraction of the nonrenewables stock, the lower production is

- To solve this *nonrenewables*-augmented Solow model (represented by equations (1)-(5) and the assumption regarding $s_E$) in terms of effective units of labor is more complicated than usual
  - because of the inclusion of $E$
- We can alternatively exploit another Kaldor's (1963) fact: along a *BGP*, the capital-output ratio is constant over time
- Dividing both sides of the production function (1) by $Y^\alpha$ we get,

$$Y(t)^{1-\alpha} = A(t)E(t)^\gamma \left[\frac{K(t)}{Y(t)}\right]^\alpha L(t)^{1-\alpha-\gamma} \tag{9}$$

- Solving for $Y$,

$$Y(t) = \left[ A(t)E(t)^{\gamma} \left[ \frac{K(t)}{Y(t)} \right]^{\alpha} L(t)^{1-\alpha-\gamma} \right]^{\frac{1}{1-\alpha}} \tag{10}$$

- Taking logs and time derivatives of eq. (10) we get,

$$\frac{\dot{Y}(t)}{Y(t)} = \frac{1}{1-\alpha} \left[ \frac{\dot{A}(t)}{A(t)} + \gamma \frac{\dot{E}(t)}{E(t)} + \alpha \underbrace{\left[ \frac{\dot{K}(t)}{K(t)} - \frac{\dot{Y}(t)}{Y(t)} \right]}_{=0 \text{ along a } BGP} + (1-\alpha-\gamma) \frac{\dot{L}(t)}{L(t)} \right] \tag{11}$$

- Using simpler notation we can re-express eq. (11) as,

$$\begin{aligned} g_Y &= \left(\frac{1}{1-\alpha}\right)[g_A - \gamma s_E + (1-\alpha-\gamma)n] \\ &= \left(\frac{1}{1-\alpha}\right)[g_A - \gamma(s_E + n)] + n \end{aligned} \quad (12)$$

- Defining $g \equiv g_A/(1-\alpha)$ and $\kappa \equiv \gamma/(1-\alpha)$,

$$g_Y = g + (1-\kappa)n - \kappa s_E \quad (13)$$

so that there is growth in aggregate output along a *BGP* as long as

$$g + n > \kappa(s_E + n)$$

- Growth in output per capita along a *BGP* can be obtained by simply subtracting $n$ from eq. (13) so that,

$$g_{\tilde{y}} = g - \kappa(s_E + n) \quad (14)$$

- What do we see in eq. (14)?

$$g_{\tilde{y}} = g - \kappa(s_E + n)$$

  - The rate of resource depletion, $s_E$, has a negative effect in long-run growth rates of per capita income
  - As in the basic Solow model, population growth, $n$, has a negative effect on the long-run growth rate of per capita income
    - ⋆ There's a catch! Whether this is true ultimately depends on $g_A$
    - ⋆ If $g_A$ is exogenous because all technologies are imported from other countries, then population has clearly a negative effect on growth
    - ⋆ If, on the other hand, $g_A$ is empirically estimated (say, because we don't understand how the generation of technology occurs), this could be problematic why?

- Looking at eq. (14)

$$g_{\tilde{y}} = g - \kappa(s_E + n)$$

  and seeing the negative effect of $s_E$ on long-run growth, one might be tempted to recommend a policy that sets $s_E = 0$

- Considering the whole picture, i.e. equations (8) and (14), one realizes that setting $s_E = 0$ would be a fatal mistake
  - ⋆ Energy is a non-substitutable input in production
  - ⇒ No energy input, no production!

- **Intertemporal trade-off in energy consumption**: raising $s_E$ has positive level effects because it raises $Y$, but negative long-run effects because it lowers $g_{\tilde{y}}$

# The Natural Resources Drag I

- Any positive amount of nonrenewable resources, although crucial for production, reduces somewhat the long-run growth rate of per capita income (*recall eq.* (14))
  - this hinges on the (questionable) assumption that renewable resources cannot compensate for the depletion of nonrenewables

- How large is this growth drag?
  - necessary to include the role of land in production
  - the growth rate of per capita output in this case is given by,

$$g_{\tilde{y}} = g - \underbrace{(\beta + \kappa)n - \kappa s_E}_{\text{growth drag}}$$

where $\beta \equiv \xi/(1-\alpha)$ and $\xi$ is the income share accrued to land

# The Natural Resources Drag II

- The growth drag of natural resources is given by,

$$(\beta + \kappa)n + \kappa s_E \tag{15}$$

  so that it is determined by the exhaustibility of land and the depletion of nonrenewables, both pressured by population

- To calculate the growth drag we first need values for parameters $\alpha, \gamma$ and $\xi$ (*e.g. we could estimate them as we did for $\alpha$ in basic Solow*)
  - Taking Nordhaus' (1992) estimates,

$$(\alpha, \gamma, \xi) = (0.2, 0.1, 0.1)$$

  - we obtain that $\beta = \kappa = 0.125$

# The Natural Resources Drag III

- Further assuming, as Nordhaus, that $s_E = 0.005$ and $n = 0.01$, and plugging corresponding values in eq. (15) we get that,

$$\begin{aligned}\text{growth drag} &= (\beta + \kappa)n + \kappa s_E \\ &= 0.25 \cdot 0.01 + 0.125 \cdot 0.005 \\ &= 0.0031\end{aligned}$$

  the growth drag is about 0.3 percentage points

- To assess how large is the growth drag one must:
  1. Take as a benchmark the actual growth rate of the economy
  2. Recall the power of compounding
     - ⋆ a quantity growing at 0.3% per year doubles approx. after 225 years

# Prices, Scarcity and Evidence I

- Key principle in economics: prices, in a competitive economy, reflect the underlying situation of a commodity
  - A scarce commodity that is in great demand should have a high price
  - This is what we expect for nonrenewables such as oil, gas, etc.
  - Is this the case?

- Assume that production is Cobb-Douglas,

$$Y = F[K, X, E, L] = K^{\alpha} X^{\beta} E^{\gamma} L^{1-\alpha-\beta-\gamma}$$

where $\alpha, \beta$ and $\gamma$ are the factor income shares of capital, land and nonrenewables, respectively

# Prices, Scarcity and Evidence II

- Also, that factors of productions are paid their marginal products:

$$F_K \equiv \frac{\partial F}{\partial K} = 0 \quad \Rightarrow \quad r = \alpha \frac{Y}{K} \tag{16}$$

$$F_X \equiv \frac{\partial F}{\partial X} = 0 \quad \Rightarrow \quad P_X = \beta \frac{Y}{X} \tag{17}$$

$$F_E \equiv \frac{\partial F}{\partial E} = 0 \quad \Rightarrow \quad P_E = \gamma \frac{Y}{E} \tag{18}$$

$$F_L \equiv \frac{\partial F}{\partial L} = 0 \quad \Rightarrow \quad w = (1 - \alpha - \beta - \gamma) \frac{Y}{L} \tag{19}$$

- Denote $v_K, v_X, v_E$ and $v_L$ as the share of total output accrued to each factor of production so that,

$$\begin{aligned}(v_K, v_X, v_E, v_L) &= (r\frac{K}{Y}, P_X\frac{X}{Y}, P_E\frac{E}{Y}, w\frac{L}{Y}) \\ &= (\alpha, \beta, \gamma, 1 - \alpha - \beta - \gamma) \qquad (20)\end{aligned}$$

# Prices, Scarcity and Evidence III

- According to

$$(v_K, v_X, v_E, v_L) = (\alpha, \beta, \gamma, 1 - \alpha - \beta - \gamma)$$

  the factor shares accrued to the different factors of production are constant over time

  - ...however, this is in contradiction with the empirical evidence (e.g. recall the transition from agriculture to manufacturing)
  - this has an impact on the calculated growth drag, *unless it share are updated yearly*

- To analyze whether prices of nonrenewables reflect its scarcity we calculate its price relative to the price of labor, i.e.

$$\frac{v_E}{v_L} = \frac{P_E E}{wL}$$

# Prices, Scarcity and Evidence IV

- Solving for $P_E/w$,

$$\frac{P_E}{w} = \frac{v_E}{v_L} \cdot \left(\frac{E}{L}\right)^{-1}$$

  - As natural resources get depleted, $E/L$ diminishes and the relative price of nonrenewables should rise (*substitution effect*)
  - This is true for land as well once we control for population growth: as population grows $X/L$ diminishes because $X$ is constant

- Let's see if the evidence supports these results...

# Prices, Scarcity and Evidence V

- No strong upward trend in the relative price of fossil fuels, contradicting the theoretical predictions
  - Reconciling theory and evidence: reserves of oil doubled from 1980 to 2010 because of new discoveries

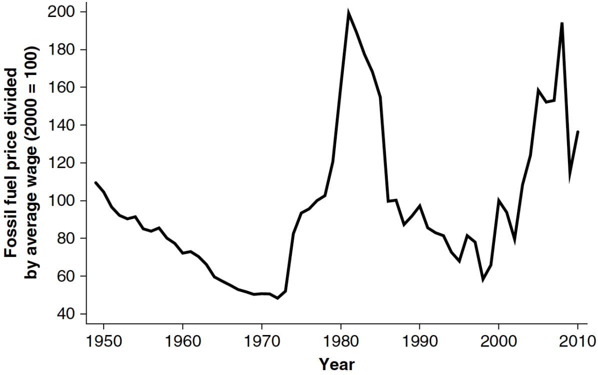
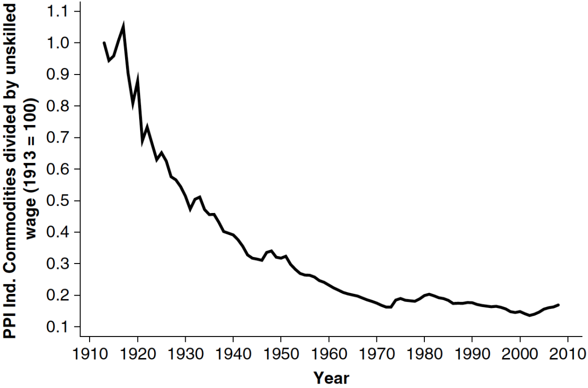



Figure: Relative price of fossil fuels in the US

# Prices, Scarcity and Evidence VI

- Strong downward trend in the relative price of industrial commodities, contradicting the theoretical predictions
  - Reconciling theory and evidence: reserves, because of discoveries, could have increased; some commodities might no be used as intensively as before; renewables might be playing an increasing and important role



# Growth, Environment and Intergenerational Welfare I

- The use of nonrenewables in production is associated with pollution
- Pollution alters ecosystems (e.g. through climate change) and likely affects health conditions of human beings (Brunekreef and Holgate, 2002; Campa and Castanas, 2008)
  - respiratory and cardiovascular diseases, lung cancer, asthmatic attacks
  - increases in mortality and hospital admissions
- Trade-off between material wellbeing and damage caused by altering the environment
- Can we model this tradeoff?
  - Yes, let's do it!

# Growth, Environment and Intergenerational Welfare II

- Assume individuals derive utility from two things:
  - material consumption, $C$
  - environmental qualtity, $R$
    - The greater $R$, the higher the environmental quality because there is less pollution

- Final utility is given by,

$$V(t) = u[C(t)] + \theta v[R(t+1)] \tag{21}$$

where $u$ and $v$ are the utility functions for consumption and environmental quality, respectively; $\theta > 0$ captures how much someone values the environment more on $\theta$

- We assume: $u^{'}[C(t)], v^{'}[R(t+1)] > 0$ and $u^{''}[C(t)], v^{''}[R(t+1)] < 0$

# Growth, Environment and Intergenerational Welfare III

- Trade-off between production and the environment because higher $C$ requires more $E$ and higher $R$ requires less $E$

- For simplicity we assume that there is no capital in production

$$Y(t) = F[A(t), E(t), L_Y(t)] = A(t)E(t)^{\gamma} L_Y(t)^{1-\gamma} \tag{22}$$

  and that everything that is produced is consumed, $Y(t) = C(t)$ so that there are no savings

- Resources in the future depend on $E$,

$$R(t+1) = R(t) - E(t) \tag{23}$$

- We can see the tradeoff: higher $E$ increases $Y$ but lowers $R$

# Growth, Environment and Intergenerational Welfare IV

- What is the optimal use of nonrenewable resources? Optimization problem:

$$\max_{E(t)} \ V(t) = u[C(t)] + \theta v[R(t+1)]$$

- FOC:

$$u^{'}[C(t)]\frac{\partial C(t)}{\partial E(t)} + \theta v^{'}[R(t+1)]\frac{\partial R(t+1)}{\partial E(t)} = 0$$

- We can obtain the partial derivatives of consumption and environment from eq. (22) and eq. (23):

$$\frac{\partial C(t)}{\partial E(t)} = \gamma A(t) B(t)^{\gamma-1} L_Y(t)^{1-\gamma} = \gamma \frac{Y(t)}{E(t)}$$

$$\frac{\partial R(t+1)}{\partial E(t)} = -1$$

- Plugging these two expressions into the FOC we obtain,

$$u^{'}[C(t)]\gamma\frac{Y(t)}{E(t)} - \theta v^{'}[R(t+1)] = 0$$

- which can be re-arranged to obtain,

$$\frac{E(t)}{Y(t)} = \frac{\gamma}{\theta} \cdot \frac{u^{'}[C(t)]}{v'[R(t+1)]} \tag{24}$$

- where $E/Y$ is the optimal ratio of resources to output
- The optimal use of energy should fall as a country gets richer!

# Growth, Environment and Intergenerational Welfare VI

- Per capita energy use in the US has been more or less stable since the 1970 (if anything, declining trend)
  - This note is reinforced if renewables have had an increasing role in production ever since

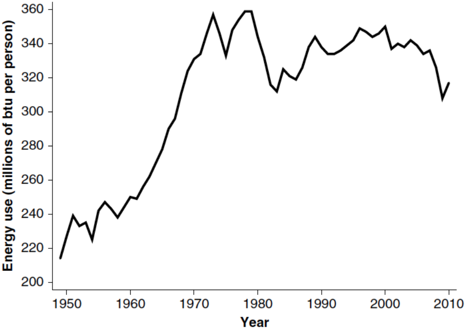



Figure: Per capita energy use in the US

- Pollution has substantially decreased in the US, whilst per capita energy use has been constant
  - This suggests that renewables have been increasingly adding energy

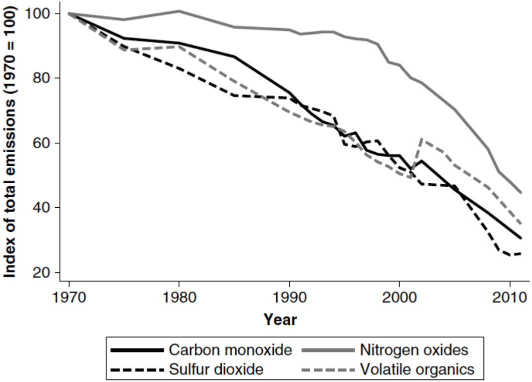
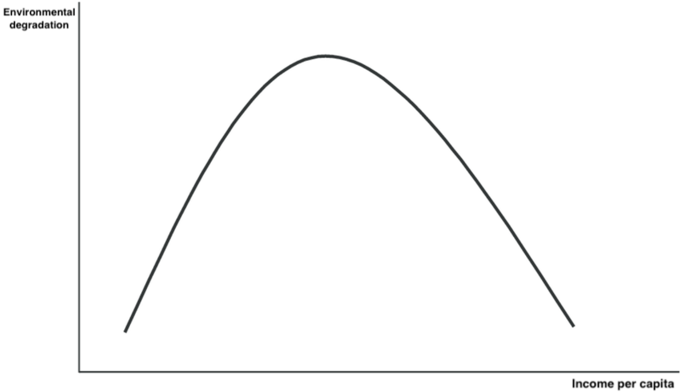



Figure: Air pollutants in the US

# Growth, Environment and Intergenerational Welfare VIII

- The tendency for pollution to fall as an economy gets richer has given rise to the concept of *environmental Kuznets curve*
- The environmental Kuznets curve suggest an inverted U-shape relationship between levels of pollution and development



In this section I present joint work with Hans Lööf on *Directed Technical Change in Energy Production*

# What have we learnt? I

Lecture 1: *Introduction*

- Facts about cross-country income differences and the world income distribution
- Empirical regularities in the economic growth process
- Proximate vs. fundamental causes of growth

Lectures 2&3: *Exogenous Growth*

- Environment and assumptions
- basic Solow model and the golden rule
- augmented Solow model with human capital
- Solow model and the data

# What have we learnt? II

Lecture 4: *Endogenous Growth I*

- First-generation models of endogenous growth
  - Harrod-Domar's
  - Frankel's
  - Lucas'
- Criticism to $1^{st}$-generation models
- Introduction to Innovation based models
  - technology, ideas, population, profits and innovation

Lectures 5&6: *Endogenous Growth II*

- Product-variety models:
  - Romer's
  - Jones'
- Schumpeterian Growth Theory
- R&D optimality

# What have we learnt? III

Lecture 7: *Technology Difussion and Trade*

- Technology transfer and club convergence
- Appropriateness of technology, skill mismatch and IPP
- A model for the autarky case
- A model with trade

Lectures 8: *Directed Technical Change*

- Market size and substitution effects
- Skill-biased technical change
- DTC and wage inequality
- DTC and the data
- Applications of DTC: pharmaceutical industry

# What have we learnt? IV

Lecture 9: *Natural Resources and Growth*

- Malthusian reasoning
- Augmented Solow with nonrenewables
- Natural resources growth drag
- Prices as indicators of scarcity and the data
- Growth, the environment and intergenerational welfare
    - Environmental Kuznets curve
- DTC and natural resources

# Written Examination

- You can find the grading scale on the syllabus for this course HT2018
- Our exam (no MCQ, as agreed):
  - similar in content to previous exams (old versions on *Canvas*)
  - 2 sections
  - Short essay questions: 30-35 points
    - can be theoretical (mathematical or not)
    - can be empirical (involve calculations)
  - Growth models: 60-65 points
    - involve mainly derivations and calculations
    - economics interpretations required
- I will allocate to days for offices hours and you can drop by my office with questions
- I won't be available during May 26-28, inclusive

# Thank you for your attention!

Course Evaluation: https://goo.gl/forms/WnkkhyJj2cZFxudJ3

# Supplemental I

- Assume that $g_A$ is empirically estimated because the process of technology generation is not well know
- Suddenly it is revealed to you in a dream that population plays a key role in the generation of technology
  - More specifically, tech. progress occurs *à la Jones*
- Going back to our original equation,

$$
\begin{aligned}
g_{\tilde{y}} &= g - \kappa(s_E + n) \\
&= \left(\frac{1}{1-\alpha}\right) g_A - \left(\frac{\gamma}{1-\alpha}\right)(s_E + n) \\
&= \left(\frac{1}{1-\alpha}\right) [g_A - \gamma(s_E + n)] \\
&= \left(\frac{1}{1-\alpha}\right) \left[\frac{\lambda n}{1-\phi} - \gamma(s_E + n)\right]
\end{aligned}
$$

# Supplemental II

- If you fully work the last expression you get,

$$g_{\tilde{y}} = \left(\frac{1}{1-\alpha}\right)\left[n\frac{\lambda+\gamma(\phi-1)}{1-\phi} - \gamma s_E\right]$$

- Whether population growth has a negative effect on the growth rate of output per capita ultimately depends on whether

$$\frac{\lambda+\gamma(\phi-1)}{1-\phi} < 0$$

back

# Supplemental III

- One of the most vibrant discussions in economics concerns integenerational welfare and natural resources
- In our model, the higher $\theta$, the fewer nonrenewables we will use in production today
- Parameter $\theta$ may be alternatively thought as the weight we assign to future generations rather than as the weight we put on our own future consumption of the environment
- Put simply, $\theta$ captures how much we value the consumption of the environment by subsequent generations
- Disagreements on environmental policy might be understood as a consequence of heterogenous values for $\theta$ across interest groups back