Non-renewable resources and climate change: Are we back to zero growth?

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Growth Theory

Introduction

- Constant growth in output per worker in the Solow model depends on the assumption that non-labor factors of production can be increased indefinitely.
- However, some important production factors are finite:
  - We will see that constant growth is still a likely outcome.
  - Moreover, price data suggests that seemingly necessary and finite resources are either not necessary or not finite.
- We also looked at the issue of pollution and the environmental Kuznets curve:
  - We will see that technological progress again gives hope for long-run economic growth.
  - We will explain the environmental Kuznets curve by transition dynamics.
- Finally, we will consider green-house gas emission.

Non-renewable resources

History

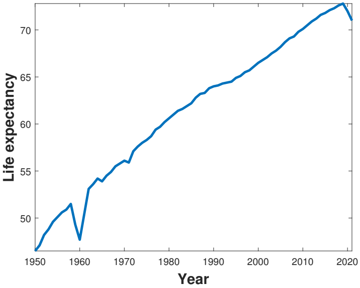
Meadows et al. (1972) in their contribution for the *Club of Rome*, conducted computer simulations for world output and population. They emphasized particularly the finite amount of some key resources which would make their use less and less feasible:

"Given present resources consumption rates and the projected increase in the rates, the great majority of the currently important nonrenewable resources will be extremely costly 100 years from now. [...] The prices of those resources with the shortest static reserve indices have already begun to increase. The price of mercury, for example, has gone up 500 percent in the last 20 years; the price of lead has increased 300 percent in the last 30 years."

History II

Ehrlich (1968) revived the Malthusian logic of a population growing faster than food supply writing:

"The battle to feed all of humanity is over. In the 1970s and 1980s hundreds of millions of people will starve to death [...]. At this late date nothing can prevent a substantial increase in the world death rate."



Source: United Nations

Overview

- We are going to introduce a non-renewable resource into the Solow model.
- You can think of oil, gas, minerals, and other things that are in finite supply but important in production.
- The key difference to capital is that these resources will be used-up over time.
- Note, this is also different from land in the Malthus model which was finite but fixed.

Production

Assume production is given by

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

where $E(t)$ is the amount of the non-renewable resource used in production. Note, the function has constant returns to scale in $K(t), E(t), L(t)$. As in the Solow model, there are different (but economically equivalent) ways to have $A(t)$ in the production function. Here, it enters with the same exponent as in the basic Solow model which will make the comparison simpler.

Factor dynamics

As before, we have

$$\frac{\dot{L}(t)}{L(t)} = n, \tag{2}$$

$$\frac{\dot{A}(t)}{A(t)} = g, \tag{3}$$

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

Dynamics of the non-renewable resource

Assume we start in period 0 with a stock of the non-renewable resource $R(0)$. We have that our use of the resource depletes its stock:

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

One can show that when competitive firms own the resource, optimal behavior implies that each period a constant fraction of the remaining stock is used:

$$s_E = \frac{E(t)}{R(t)}. \tag{6}$$

Hence, the stock must decline over time at rate s_E:

$$\frac{\dot{R}(t)}{R(t)} = -s_E = \frac{\dot{E}(t)}{E(t)}. \tag{7}$$

Dynamics of the non-renewable resource II

$$\frac{\dot{R}(t)}{R(t)} = -s_E. \tag{8}$$

We know the solution to this differential equation:

$$R(t) = R(0)\exp(-s_E t). \tag{9}$$

That is, the stock is declining exponentially over time. Finally, as $E(t) = s_E R(t)$, we know that consumption of the resource is declining exponentially over time:

$$E(t) = s_E R(0)\exp(-s_E t). \tag{10}$$

The steady state

We begin again with analyzing behavior in steady state. As before, we first find the capital-to-output ratio in steady state:

$$z(t) = \frac{K(t)}{Y(t)} = \frac{K(t)^{1-\alpha}}{A(t)^{1-\alpha}E(t)^{\gamma}L(t)^{1-\alpha-\gamma}} \tag{11}$$

$$\frac{\dot{z}(t)}{z(t)} = (1-\alpha)\frac{\dot{K}(t)}{K(t)} - (1-\alpha)g + \gamma s_E - (1-\alpha-\gamma)n. \tag{12}$$

Hence, in steady state,

$$0 = \left(\frac{\dot{K}(t)}{K(t)}\right)^{*} - g + \frac{\gamma}{(1-\alpha)}s_E - \frac{(1-\alpha-\gamma)}{(1-\alpha)}n. \tag{13}$$

The steady state capital-to-output ratio

From the capital-accumulation equation, we have

$$\dot{K}(t) = sA(t)^{1-\alpha}K(t)^{\alpha}E(t)^{\gamma}L(t)^{1-\alpha-\gamma} - \delta K(t) \tag{14}$$

$$\frac{\dot{K}(t)}{K(t)} = \frac{s}{z(t)} - \delta \tag{15}$$

Putting things together,

$$n + g - \frac{\gamma}{(1-\alpha)}(n + s_E) = \frac{s}{z^*} - \delta \tag{16}$$

$$z^* = \frac{s}{n + g + \delta - \frac{\gamma}{(1-\alpha)}(n + s_E)}, \tag{17}$$

which is indeed constant.

Output in steady state

We need to rewrite the production function in terms of the capital output ratio:

$$Y(t) = A(t)^{1-\alpha} K(t)^{\alpha} E(t)^{\gamma} L(t)^{1-\alpha-\gamma} \tag{18}$$

$$Y(t)^{1-\alpha} = A(t)^{1-\alpha} \left(\frac{K(t)}{Y(t)}\right)^{\alpha} E(t)^{\gamma} L(t)^{1-\alpha-\gamma} \tag{19}$$

$$Y(t) = A(t) \left(\frac{K(t)}{Y(t)}\right)^{\frac{\alpha}{1-\alpha}} E(t)^{\frac{\gamma}{1-\alpha}} L(t)^{1-\frac{\gamma}{1-\alpha}} \tag{20}$$

$$Y(t) = A(t) \left(\frac{K(t)}{Y(t)}\right)^{\frac{\alpha}{1-\alpha}} \left(s_E R(0) \exp(-s_E t)\right)^{\frac{\gamma}{1-\alpha}} L(t)^{1-\frac{\gamma}{1-\alpha}} \tag{21}$$

Output per worker in steady state

$$y(t)^* = \left(\frac{s}{n + g + \delta - \frac{\gamma}{(1-\alpha)}(n + s_E)} \right)^{\frac{\alpha}{1-\alpha}} \left(s_E R(0) \exp(-s_E t)\right)^{\frac{\gamma}{1-\alpha}} L(t)^{-\frac{\gamma}{1-\alpha}} A(t) \quad (22)$$

Note, the depletion rate s_E enters three times into the expression. A higher depletion rate (i) increases the capital-to-output ratio, (ii) raises the resource use and, thereby, production, and (iii) reduces the stock of resources over time and, thereby the resource use.

Output growth in steady state

Taking logs and the derivative with respect to time yields output growth:

$$Y(t) = A(t)\left(\frac{K(t)}{Y(t)}\right)^{\frac{\alpha}{1-\alpha}} (s_E R(0)\exp(-s_E t))^{\frac{\gamma}{1-\alpha}} L(t)^{1-\frac{\gamma}{1-\alpha}}$$

$$\begin{aligned}\ln Y(t)^* &= \ln A(t) + \frac{\alpha}{1-\alpha}\ln\left(\frac{K(t)}{Y(t)}\right)^* \\ &\quad + \frac{\gamma}{1-\alpha}(\ln(s_E R(0)) - s_E t) + \left(1 - \frac{\gamma}{1-\alpha}\right)\ln L(t)\end{aligned}$$

$$\left(\frac{\dot{Y}(t)}{Y(t)}\right)^* = g + n - \frac{\gamma}{1-\alpha}(s_E + n).$$

Output growth in steady state II

$$\left(\frac{\dot{Y}(t)}{Y(t)}\right)^{*} = g + n - \frac{\gamma}{1-\alpha}(s_E + n).$$

- The depletion rate acts like negative technological progress on growth as the non-renewable resource becomes more scarce over time.
- Labor contributes to growth with a rate $< n$. Due to the fixed factor, as in the Malthus model, population growth reduces worker's productivity over time.

Output per worker growth in steady state

Instead of total output, we can also look at output per capita:

$$y(t) = \frac{Y(t)}{L(t)} = A(t)\left(\frac{K(t)}{Y(t)}\right)^{\frac{\alpha}{1-\alpha}} (s_E R(0)\exp(-s_E t))^{\frac{\gamma}{1-\alpha}} L(t)^{-\frac{\gamma}{1-\alpha}}$$

$$\left(\frac{\dot{y}(t)}{y(t)}\right)^* = g - \frac{\gamma}{1-\alpha}(s_E + n).$$

The depletion rate has the same negative effect on output per capita as the population growth rate. Both reduce the efficiency of labor over time. We have positive growth in GDP per capita iff

$$g > \frac{\gamma}{1-\alpha}(s_E + n).$$

The price of non-renewables over time

Given our Cobb-Douglas production function, the share of income going to non-renewables should be constant over time:

$$P_E(t)E(t) = \gamma Y(t)$$
$$P_E(t) = \gamma \frac{Y(t)}{E(t)}.$$

Take logs and the derivative with respect to time gives the growth rate in non-renewable prices:

$$\frac{\dot{P}_E(t)}{P_E(t)} = \frac{\dot{Y}(t)}{Y(t)} - \frac{\dot{E}(t)}{E(t)}$$
$$\frac{\dot{P}_E(t)}{P_E(t)} = g - \frac{\gamma}{1-\alpha} s_E + \left(1 - \frac{\gamma}{1-\alpha}\right) n + s_E$$
$$\frac{\dot{P}_E(t)}{P_E(t)} = g + \left(1 - \frac{\gamma}{1-\alpha}\right)(n + s_E).$$

The price of non-renewables over time II

$$\frac{\dot{P}_E(t)}{P_E(t)} = g + \left(1 - \frac{\gamma}{1-\alpha}\right)(n + s_E)$$
$$\frac{\dot{P}_E(t)}{P_E(t)} = g + \frac{1-\alpha-\gamma}{1-\alpha}(n + s_E) > 0$$

The price of non-renewables rises over time for three reasons:

- Technological progress makes non-renewables more productive over time.
- Population growth makes non-renewables more productive over time.
- The falling stock of non-renewables makes them more productive over time.

The price of non-renewables relative to labor

To compare the predictions of the model, it is simpler to look at relative prices. Given constant factor shares, we have:

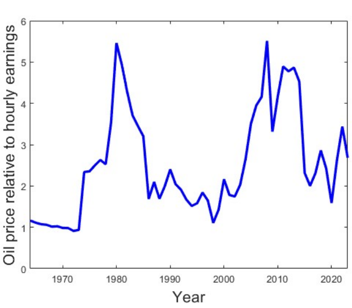
$$\frac{P_E(t)E(t)}{w(t)L(t)} = \frac{\gamma Y(t)}{(1-\gamma-\alpha)Y(t)}$$
$$\frac{P_E(t)}{w(t)} = \frac{\gamma}{(1-\gamma-\alpha)}\frac{L(t)}{E(t)} = \frac{\gamma}{(1-\gamma-\alpha)}\frac{L(0)\exp(nt)}{s_E R(0)\exp(-s_E t)}$$

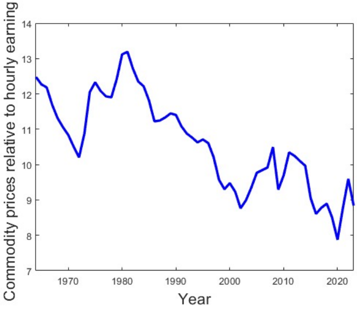
Next, take logs and the derivative with respect to time to get the growth rate in the price wage ratio, $RP(t) = \frac{P_E(t)}{w(t)}$:

$$\frac{\dot{R}P(t)}{RP(t)} = n + s_E.$$

With $n > 0$, resources become more scarce over time relative to labor implying that their relative price is growing.

Price of commodities





Source: St. Louis Fed

Instead of rising prices for non-renewables relative to wages, we have, if any, falling prices.

Why the predictions fail

The resource is not non-renewable:

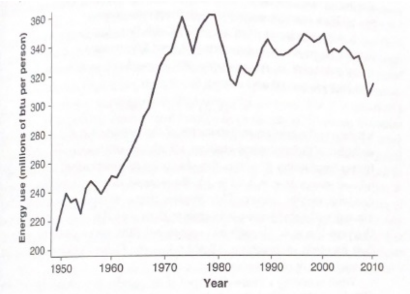
- practically, some resources are close to infinite, they just become more expensive to mine (at the current technology).
  - The amount of proven oil reserves doubled between 1980 and 2009.
  - So far, we mined 700 million metric tons of copper. Estimates are that 6.3 billion are still in the earth crust. Next, we may go to space.
- at a higher level of abstraction, physics tells us that we do not use-up anything, we simply transform material into other material that is of more use to us. How good we are in this depends on our technology, i.e., recipes.

The stock of non-renewables

Mineral	1950 Reserves	Production 1950–2000	2000 Reserves
Tin	6	11	10
Copper	100	339	340
Iron Ore	19,000	37,583	140,000
Lead	40	150	64
Zinc	70	266	190

Source: Blackman and Baumol (2008)

Consumption of commodities



In fact, we do not observe a slow-down in the use of non-renewables.

Why the predictions fail II

The resource is not essential: Simon (1980) provides a good example from history:

In the 16th century, most ships were build out of wood leading to deforestation of large parts in Europe.

$\Rightarrow$ The price of wood rose leading to incentives to innovate by using other materials.

$\Rightarrow$ Over time, ships were build out of iron and later steel. Moreover, we invented ways to recycle these resources.

Accordingly, Simon (1980) identifies human ingenuity as the ultimate resource.

A green Solow Model

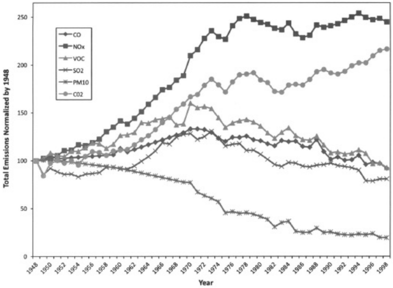
- One may think of the environment as a non-renewable resource. As pollution increases, the resource becomes depleted.
- Pollution may be best thought of something we can pay resources for to avoid it:
  - Use production technologies that create less pollution (energy) but are more expensive.
  - Create energy from green, expensive sources.
- Brock and Taylor (2010) present data on pollution and a model to understand the data.
- After understanding the flow of pollution, we will think about the stock, i.e., the environment.

Data facts about pollution

Brock and Taylor (2010) highlight 3 data facts about pollution:

1. Pollution increases initially with per capita income but starts falling at some point, an environmental Kuznets Curve.
2. Pollution per unit produced falls over time.
3. Abatement costs are a small, constant share of national output.

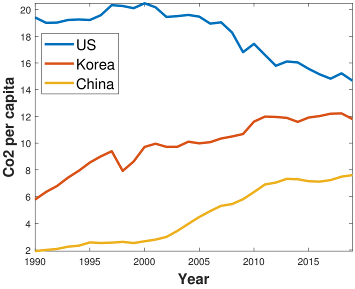
An environmental Kuznets Curve



Source: Brock and Taylor (2010)

In the US, despite income growth, most pollutant emissions are falling since 1984.

An environmental Kuznets Curve II



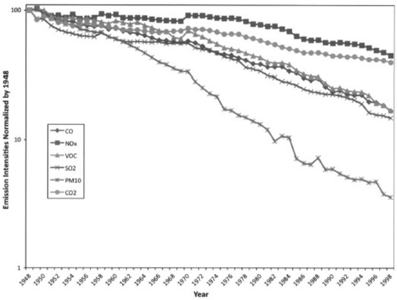
Source: World Bank

Since 2000, this is also true for $CO2$ emissions. Poorer countries still increase their emission levels.

An environmental Kuznets Curve III

In 1952 and 1969, a section of the Cuhayoga river in Ohio was so covered in oil that it caught fire. The latter incident contributed to amendments to the Clean Water Act and the founding of the federal Environmental Protection Agency.

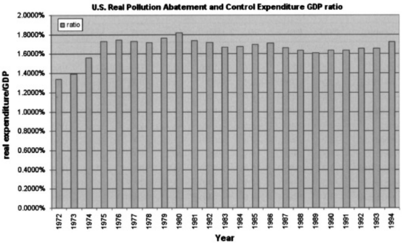
Falling emission intensity



Source: Brock and Taylor (2010)

- Emissions per units produced are falling over time for a large variety of emissions.
- The growth rate is close to constant over time.

Constant cost share of abatement



Source: Brock and Taylor (2010)

Since 1975, the abatement costs as share of GDP have been constant around 1.7%.

What are the implications from this data?

You may think that as we become richer, we can divert more resources to abatement, i.e., the environment is a luxury good. But

- this would imply that the cost share of abatement should rise as we become richer.

Instead, a constant cost share with increasing abatement suggests that we become more productive over time in abatement.

- We develop less resource-intensive production technologies.
- We switch to goods that are less resource intensive.

A model of emissions over time

- We are now ready to think about a model of emissions over time.
- The production side and capital accumulation side are as in the Solow model.
- We add to this that production creates pollution.
- We can undergo abatement to reduce the pollution but this reduces our consumption.
- Improvements in the abatement technology are the key for long-run emission dynamics.

Production and capital accumulation

We use again a Cobb-Douglas production function:

$$Y(t) = K(t)^{\alpha} \left(A(t)L(t)\right)^{1-\alpha} \tag{23}$$

with our familiar laws of motions:

$$\frac{\dot{L}(t)}{L(t)} = n \tag{24}$$

$$\frac{\dot{A}(t)}{A(t)} = g. \tag{25}$$

Pollution and abatement

Each unit of output Y creates Ω units of pollution. How much of this pollution is emitted depends on the total amount of abatement:

$$E(t) = Y(t)\Omega(t) - \Omega(t)B(t). \tag{26}$$

We assume that the amount of abatement, B, is a constant returns to scale function depending on total output and the effort we put into abatement, $\theta Y(t)$:

$$B(t) = B(Y(t), \theta Y(t)). \tag{27}$$

Idea:

- The more we produce, i.e., pollute, the more we can reduce emissions.
- The amount we reduce pollutants depends on our effort.

Emissions over time

$$E(t) = Y(t)\Omega(t) - \Omega(t)B(Y(t), \theta Y(t)) \tag{28}$$

$$E(t) = Y(t)\Omega(t)\left[1 - B(1,\theta)\right] \tag{29}$$

Hence, emissions per unit produced are

$$\frac{E(t)}{Y(t)} = \Omega(t)\left[1 - B(1,\theta)\right] \tag{30}$$

We have seen that, in the data, $\frac{E(t)}{Y(t)}$ is decreasing at a constant rate, and θ is constant. Hence, to match the data, we need $\Omega(t)$ to grow at a negative rate:

$$\Omega(t) = \Omega(0)\exp(-g_B t). \tag{31}$$

The national income identity, and capital dynamics

Given that we use $\theta Y(t)$ on abatement, we have for consumption and investment:

$$I(t) + C(t) = (1 - \theta)Y(t). \tag{32}$$

Hence, the law of motion for capital is

$$\dot{K}(t) = (1 - \theta)sK(t)^{\alpha}\left(A(t)L(t)\right)^{1-\alpha} - \delta K(t) \tag{33}$$

Steady state capital-to-output ratio

As before, to analyze the steady state, we derive the capital-to-output ratio:

$$z(t) = \frac{K(t)}{Y(t)} = \frac{K(t)}{K(t)^{\alpha}\left(A(t)L(t)\right)^{1-\alpha}} \tag{34}$$

$$= \left(\frac{K(t)}{A(t)L(t)}\right)^{1-\alpha}. \tag{35}$$

implying that the growth rate is

$$\frac{\dot{z}(t)}{z(t)} = (1-\alpha)\frac{\dot{K}(t)}{K(t)} - (1-\alpha)(n+g) \tag{36}$$

$$\left(\frac{\dot{K}(t)}{K(t)}\right)^{*} = n+g \tag{37}$$

Solving for the steady state

$$z^* = \left(\frac{K(t)}{Y(t)}\right)^* = \frac{s(1-\theta)}{n+g+\delta}. \tag{38}$$

Hence, output per worker and consumption per worker in steady state are

$$y(t)^* = \left(\frac{s(1-\theta)}{n+g+\delta}\right)^{\frac{\alpha}{1-\alpha}} A(t) \tag{39}$$

$$c(t)^* = (1-s)(1-\theta)\left(\frac{s(1-\theta)}{n+g+\delta}\right)^{\frac{\alpha}{1-\alpha}} A(t). \tag{40}$$

Steady state consumption and abatement effort

$$y(t)^* = \left(\frac{s(1-\theta)}{n+g+\delta}\right)^{\frac{\alpha}{1-\alpha}} A(t) \quad (41)$$

$$c(t)^* = (1-s)(1-\theta)\left(\frac{s(1-\theta)}{n+g+\delta}\right)^{\frac{\alpha}{1-\alpha}} A(t) \quad (42)$$

A higher abatement effort reduces consumption per worker for two reasons:

- after abatement, less output is left over for consumption.
- higher abatement reduces capital investment and, hence, the capital-to-output ratio and, thereby, output per worker.

Pollution growth in steady state

We can derive the growth rate of output as in the standard Solow model

$$Y(t) = \left(\frac{K(t)}{Y(t)}\right)^{\frac{\alpha}{1-\alpha}} A(t)L(t) \tag{43}$$

$$\Rightarrow \left(\frac{\dot{Y}(t)}{Y(t)}\right)^{*} = n + g. \tag{44}$$

From $E(t) = Y(t)\Omega(t)\left[1 - B(1,\theta)\right]$ we have in steady state

$$g_E^{*} = \left(\frac{\dot{E}(t)}{E(t)}\right)^{*} = n + g - g_B. \tag{45}$$

Whether total emissions fall in steady state depends on the race between output growth and the growth rate of emissions per output. The U.S. data suggests that in steady state, total emissions fall, i.e., $g_B > n + g$.

Pollution growth outside the steady state

Again, we, first, need to know output growth

$$Y(t) = \left(\frac{K(t)}{Y(t)}\right)^{\frac{\alpha}{1-\alpha}} A(t)L(t) \tag{46}$$

$$\frac{\dot{Y}(t)}{Y(t)} = \frac{\alpha}{1-\alpha}\frac{\dot{z}(t)}{z(t)} + g + n. \tag{47}$$

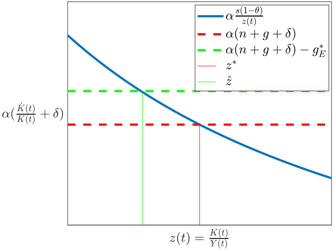
and, hence,

$$E(t) = Y(t)\Omega(t)\left[1 - B(1,\theta)\right] \tag{48}$$

$$\frac{\dot{E}(t)}{E(t)} = g_E^* + \frac{\alpha}{1-\alpha}\frac{\dot{z}(t)}{z(t)}. \tag{49}$$

When the capital-to-output ratio grows, output grows and, thus, emissions grow faster than in steady state.

The environmental Kuznets curve



- At z^*, $\alpha \frac{s(1-\theta)}{z(t)} = \alpha(\delta + n + g)$, we are in steady state, and $\frac{\dot{E}(t)}{E(t)} = g_E^*$.
- At $\hat{z}$, $\alpha \frac{s(1-\theta)}{z(t)} - \alpha(\delta + n + g) = \frac{\alpha}{1-\alpha} \frac{\dot{z}(t)}{z(t)} = -g_E^*$, i.e., emission growth is zero.
- At any point to the left of $\hat{z}$, emission growth is positive, to the right, it is negative.
- As poor countries converge to steady state, their emission growth is falling.

Convergence to steady state

It is straight forward to show that

$$z(t) = \frac{s(1-\theta)}{n+g+\delta} + \left[z(0) - \frac{s(1-\theta)}{n+g+\delta}\right]\exp(-\beta t) \tag{50}$$

$$\beta = (1-\alpha)(n+g+\delta). \tag{51}$$

As in the Solow model, the growth rate of the capital-to-output ratio is fastest the further is an economy below its steady state. As

$$\frac{\dot{E}(t)}{E(t)} = g_E^* + \frac{\alpha}{1-\alpha}\frac{\dot{z}(t)}{z(t)}, \tag{52}$$

emission growth will be fastest for economies well below their steady states and will slow down over time as output growth slows down.

Convergence to steady state II

We can also consider the implications for a developed economy that increases its abatement effort.

$$z(t) = \frac{s(1-\theta)}{n+g+\delta} + \left[z(0) - \frac{s(1-\theta)}{n+g+\delta} \right] \exp(-\beta t) \tag{53}$$

$$\beta = (1-\alpha)(n+g+\delta). \tag{54}$$

- The growth rate of the capital-to-output ratio will be most negative directly after the policy change.
- $\Rightarrow$ The growth rate of output will be lowest directly after the policy change.
- $\Rightarrow$ The growth rate of pollution will be most negative directly after the policy change.

From emissions to climate change

- The model helps us to understand emissions over time.
- We will now look at a model where emissions lead to climate change that reduces output.
- Unfortunately, we will have to rely on numerical simulations to solve the model.

Production

We use again a Cobb-Douglas production function, where emissions increase output:

$$Y(t) = \frac{E(t)^{\gamma}}{\exp(\theta D(t))} K(t)^{\alpha} \left(A(t)L(t)\right)^{1-\alpha-\gamma}. \tag{55}$$

Higher emissions allow for more output through cheaper production:

- Fossil energy sources are cheaper and easier to manage than renewables.
- Less need for abatement.

The damage function

$D(t)$ is a function of environmental damage (temperature) that is caused by emissions:

$$\dot{D}(t) = E(t) - \delta_D D(t), \tag{56}$$

where δ_D measures the natural (or man-made) depreciation of emissions in the air.

The damage function II

- The economic costs of global warming are heavily debated. What is clear, they are place dependent.
  - The most obvious costs are desertification of farmland. However, at the same time, Siberia and Canada will become viable alternatives.
  - Air conditioning will have to become more prevalent in some countries but we will save on heating in other countries.
  - Besides effects on production, there may be other utility costs of climate change.

The damage function III

- Overall, the costs of climate change will depend a lot on how good we are in reallocating production to regions that benefit.
  - The most affected regions will be in the south: The effects of migration from the south will depend on how well immigration systems in the north work.
  - Green energy could be relatively cheap if the north could put up solar farms (capital) in the south.
- I won't attempt to quantify these costs, but will only use the model to highlight some economic trade-offs.

Laws of motion

Using the insights from our treatment of abatement, I will assume emissions are declining over time:

$$\frac{\dot{E}(t)}{E(t)} = -g_E. \tag{57}$$

Finally, we have population growth, technological progress, and capital accumulation:

$$\frac{\dot{L}(t)}{L(t)} = n, \tag{58}$$

$$\frac{\dot{A}(t)}{A(t)} = g, \tag{59}$$

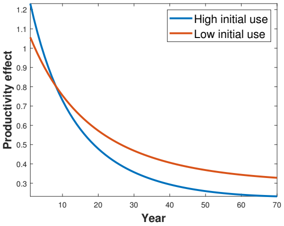
$$\dot{K}(t) = sY(t) - \delta K(t). \tag{60}$$

The very long-run steady state

As the growth in emissions is negative, both $E(t)$ and $D(t)$ will converge to zero and, hence, we have in the long run our model of a non-renewable resource which use declines at a constant rate:

$$Y(t) = E(t)^{\gamma} K(t)^{\alpha} \left(A(t)L(t)\right)^{1-\alpha-\gamma} . \tag{61}$$

The race between cheap production and environmental damage

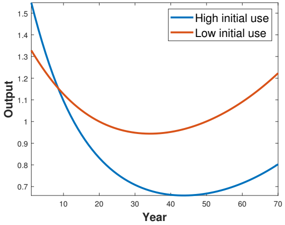


While converging to this steady state, labor productivity will change over time. The total productivity effect of emissions is

$$\frac{E(t)^{\gamma}}{\exp(\theta D(t))}. \tag{62}$$

A high level of initial emissions boosts output today but, by accumulating environmental damage, reduces output in the future.

Output over time



Initially, higher emissions lead to higher output. However, over time, output is lower because environmental damage is higher.

Should we reduce emissions today?

- The answer depends on the question how much we value resources (consumption) today relative to the future.
- The most prominent economic climate change models suggest that we have to have low discount rates to justify the costs of emission reduction: $0.96^{100} < 0.02$.
- How should we discount the future: Ultimately, the answer depends on the question on how much we value future generations.
- One may take the stance that we should not discount the well-being of future generations at all. However, in that case, it is hard to explain why we save so little physical capital (remember, the MPK is much higher than suggested by the golden rule).

Taking stock: are we back to zero growth?

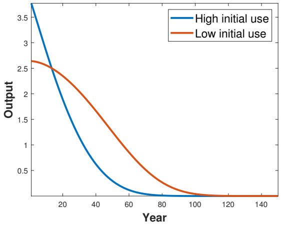
The problem of overusing a factor sounds very familiar to models of fixed (finite) factors. Yet, we have overcome the Malthus poverty trap and the scarcity of other finite factors of production. Should we expect the same with pollution?

In the abstract, we can again overcome the scarcity problem by using green energies or abatement. Just as in the Solow model, this is something we can invest in (no longer a fixed factor) and theoretically in infinite supply (the sun).

What makes the problem more difficult are missing property rights. With other non-renewable resources, prices rise when the resource experiences shortage. With pollution, we have a *tragedy of the common*.

In the cases of water and air pollution, the problem may be solvable at the national level through taxes and regulations. However, green house gases require an international solution.

The assumption of emission reductions



I have assumed throughout that emissions will not increase in the future. If they increase too fast, the model implies that the economy will be destroyed irrespective of the initial level of emissions.

Environment and growth

The Nobel price winning economist Nordhaus warns in Nordhaus et al. (1992) to translate lessons from other non-renewables one-to-one to the case of green-house gases:

"Economists have often belied their tradition as the dismal science by downplaying both earlier concerns about the limitations from exhaustible resources and the current alarm about potential environmental catastrophe. However, to dismiss today's ecological concerns out of hand would be reckless. Because boys have mistakenly cried wolf in the past does not mean that the woods are safe."

Back to our three big questions

1. Why are we so rich and they so poor?
   - Different saving rates, population growth rates, resource stocks and resource use rates, and technology levels.
2. Why are there growth miracles?
   - Rapid accumulation of physical capital.
3. What are the engines of long-run economic growth?
   - Technological progress and abatement progress on the positive, population growth and resource use on the negative.

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