Marginal Benefits of Population: Evidence from a Malthusian Semi-Endogenous Growth Model*

Maya Eden[†] Kevin Kuruc[‡]

June 25, 2023

Abstract

The relationship between human population sizes and per capita consumption has been long debated. We revisit this question by bringing data to bear on a parsimonious model with fixed natural resources and non-rival innovation—the countervailing forces invoked as first-order considerations. A sufficient statistic for the (local) relationship between long-run per capita income and population sizes depends on the income share of natural resources, a share that is small and non-increasing in the data. This suggests that the economy (locally) exhibits increasing returns to scale, on net, and will continue to for plausible population sizes of the upcoming century.

JEL Codes: O44; O30; Q56; J11.

Keywords: Malthusian constraints, scale effects, innovation, endogenous growth, natural resources, optimal population.

*We would like to thank Oded Galor, Mike Geruso, Chad Jones, Marta Prato, Dean Spears, David Weil, Mu-Jeung Yang, Anson Zhou and participants at the Global Priorities Institute's Workshops on Global Priorities Research, the University of Texas Macroeconomics Workshop, and the Population Wellbeing Initiative's Innovation and Scale Workshop for conversations and comments that have greatly improved the paper. Gage Weston provided excellent research assistance. All remaining errors are our own.

[†]Brandeis University; CEPR; Global Priorities Institute, University of Oxford. Email: meden@brandeis.edu

[‡]University of Texas at Austin; Global Priorities Institute, University of Oxford. Email: kevinkuruc@utexas.edu.

1 Introduction

Dating back to Malthus's (1798) *An Essay on the Principle of Population* scholars have speculated about the relationship between population sizes and per capita outcomes. The classic Malthusian concern is that, in the presence of a fixed factor in production, the economy exhibits decreasing returns to scale. Each additional worker gets less of this factor which decreases average labor productivity (and, hence, per capita income). More recently, economists have come to recognize important channels by which a larger population could have competing benefits. Paul Romer's work is perhaps the most notable and frequently cited example. Knowledge, the driver of efficiency improvements, is both (i) increasing in the size of the population and (ii) infinitely shareable. This generates increasing returns to scale (Romer, 1990; Jones, 2005). Understanding whether on net—and at which population sizes—the economy exhibits increasing or decreasing returns to scale remains an important open question, especially as societies with enduring low fertility consider the implications of population decline.

This paper makes progress on this question in two steps. First, we propose a general model that includes the two key aforementioned ingredients—fixed natural resources and a population-productivity relationship—and gives rise to a sufficient statistic that governs the relationship between per capita income and the size of the population. Second, we leverage existing data and recent empirical estimates to document the sign, level, and trend of this sufficient statistic. This analysis produces three main results, together pointing towards a positive relationship between population sizes and long-run per capita consumption.

The first result is analytical: the sign of the relationship between population size and per capita incomes is determined by the difference between the income share of natural resources and the elasticity of productivity with respect to populations. That the income share of natural resources is important for quantifying the Malthusian channel has been documented in the special case of CES production (Weil and Wilde, 2009); our framework extends this to any constant returns to scale (in rival inputs) production function. An analytical solution for the productivity-population relationship is less straightforward because population sizes have growth, rather than level, effects—a mismatch that we suspect has contributed to the lack of productive dialogue between these literatures. An innovation of this paper is to introduce a simple relaxation of the idea-generating equation that leads to a zero-growth balanced growth path (i.e., a steady-state) with an analytical solution for per capita consumption. This allows us to compare the (eventual) level benefits of additional innovation against the level costs of natural resources.

The next two findings result from bringing empirics to bear on these terms. First, the income share of natural resources is small in the modern global economy. Aggregating data on rents earned by different resources—e.g., timber, minerals, energy sources, agricultural land—from the World Bank and U.S. Department of Agriculture, we construct a time-series over the last half-century for a measure of total natural resource income. This measure sits between 2-8% of global GDP, reaching the higher end of that range only temporarily during well-known energy price spikes. Conservative calibrations based on existing empirical results of the population-productivity channel imply significantly larger gains than the implied losses in per capita consumption coming from spreading natural resources more widely. The main finding of the paper is that at current and observed population sizes the (local) effect of populations on income appears to be positive.

The baseline model is intentionally simple to draw out the implications of the most straightforward combination of the two dominant forces. We proceed to demonstrate that the finding of on-net of the increasing returns continues to arise in extensions of this simple model. In particular, we study model extensions with directed technological change à la Acemoglu et al. (2012), exhaustible (rather than fixed) factors in production, and competing non-rival *benefits* from ecosystem health à la Dasgupta (2021). All retain, or strengthen, the main finding.

With a few additional assumptions, our framework is equipped to speak to whether it is plausible that the local positive relationship reverses at the larger populations. There is no conceptual reason that the local relationship could not be positive at 8 billion and negative at 10 billion, where the global population is projected to end up this century. The trend of the natural resource income share can provide evidence as to when, if ever, the Malthusian channel will be large enough to dominate the benefits of additional non-rival goods. In fact, this share has been remarkably stable over the last half-century: the respective estimates in 1970 and in 2019 both sit between 2.5-3%, even as the global population has more than doubled. The natural resource income share would itself need to more than double to reverse the main finding for a 25% increase in the population. Considering that there has yet to be observable growth in this share, it seems unlikely that our local results would fail to hold for these plausible population sizes.

1.1 Relationship to existing literature

This paper sits closely to and draws from work on agglomeration and innovation benefits coming from increased population sizes, density, or growth rates. Recent notable work on this topic includes Desmet et al. (2018); Jones (2022); Peters and Walsh (2021); Peters (2022); Gross and Klein

(2023). Peters (2022) is especially relevant in its focus on population size differences and explicit accounting for fixed factors in production. Crucially our approach complements Peters' by attempting to generalize in a parsimonious way what he learns from a localized case in immediately-post-war rural Germany. Aside from this recent work there is of course a long history of studying the benefits of agglomeration and specialization that comes with larger populations in both the economic geography and economic growth literatures.

Methodologically, our approach has similarities with an earlier literature studying the transition from a Malthusian growth regime—with stagnant incomes and relatively small populations—to a modern growth regime with unprecedented growth in both incomes and populations (e.g., Kremer, 1993; Galor and Weil, 2000; Jones, 2001; Galor, 2011). These models similarly rely on a fixed factor and productivity that increases in the size of the population. A difference in this paper is our forward-looking focus, which leads us to take a few noteworthy modeling departures. Most consequentially, we study different long-run population *levels*. Global rates of population growth are expected to fall to or below zero this century: the most relevant questions are now about implications of stabilizing at different levels, not faster or slower growth rates. Conceptually, this has the advantage of allowing us to avoid modeling fertility decisions and human capital investments that may depend on this (e.g., Galor and Weil, 2000): If populations stabilize *anywhere*, fertility decisions must converge to one child per adult-lifetime, and hence common per capita child-raising costs.[1] The objective of this paper is not to predict where world populations will settle but to ask whether an increase in population sizes would increase or decrease long-run per capita incomes.

A few recent and closely related papers share our forward-looking focus as well as an interest in long-run population levels (as opposed to growth rates). Dasgupta (2019) and Córdoba et al. (2022) study the optimal population level in the face of a finite resource. However, neither allows for a positive relationship between population and technology. Instead, the models assume a Malthusian environment with decreasing returns, but the social planner values the existences of potential people. Larger populations have intrinsic value in these frameworks because of the additional existences, but have lower average living standards, generating the trade-off studied. Similarly, Pindyck (2022) characterizes sustainable consumption paths conditional on a given relationship between per capita productivity and population. Our objective is complementary to these

[1]This is in contrast to a BGP with slower or faster population growth: on a BGP with faster population growth the parent:child relationship is permanently worse than one with slower population growth, perhaps resulting in lower per capita human capital investment. This mechanism is at the core of Unified Growth Theory (Galor and Weil, 2000; Galor, 2011) and can lead to different takeaways than standard semi-engodegenous models without this explicit human capital decision.

papers, studying whether (and at what population sizes) a trade-off exists between population size and per capita consumption. Peretto and Valente (2015) is likewise closely related, adding a finite resource to a Schumpeterian model of growth and studying long-run solutions with stable populations. While sharing much of our motivation regarding non-perpetual population growth/decline, they instead focus on modeling fertility with the explicit objective of highlighting under what conditions a stable solution exists (as opposed to endogenous explosion/collapse of populations). They say less about the question of whether per capita incomes would in fact be higher or lower for larger or smaller long-run populations, a question that will be of relevance should governments want to arrest an endogenously occurring dynamic of persistent population decline.

2 The Model

This section presents the simplest model that illustrates the main point of the paper using two key equations.

$$Y = AF(N, \bar{E}) \tag{1}$$

$$\frac{\dot{A}}{A} = \alpha N^{\lambda} A^{-\beta} - \delta_A \tag{2}$$

A renewable resource problem gives rise to a Malthusian aggregate production function that has constant returns to scale in rival inputs and includes a fixed factor, $\bar{E}$. Total factor productivity, A, is Hicks-neutral and increases in population sizes, as in much of the endogenous growth literature. N represents the human population, but can generally be seen to incorporate factors that scale with it, such as physical and human capital.[2] These model components are detailed in turn.

2.1 The Malthusian Component

In traditional Malthusian models designed to describe the pre-industrial world it is standard to include a fixed factor in production representing arable land (e.g., Kremer, 1993; Galor and Weil, 2000; Jones, 2001; Vollrath, 2012; Córdoba and Liu, 2022). The modern world is more complex. Concerns over non-renewable resources, climate change, loss of biodiversity, etc., have replaced concerns about the quantity of productive soil. However, in a recent treatise on the economics of

[2]For example, suppose that N is a Cobb-Douglas aggregator of capital and labor. Standard Solow-type models tell us that capital should approximately scale with labor. In this case N would be proportional to population.

biodiversity, Dasgupta (2021) argues that management and withdrawal from the biosphere can be roughly conceptualized as a renewable resource problem. If nature is undisturbed most resources will regenerate.

Formally, assume there are three types of natural resources, respectively representing (i) exhaustible and non-renewable resources (e.g., fossil fuels); (ii) exhaustible, but renewable resources (e.g., timber, fish stocks); and (iii) non-exhaustible, but finite, resources (e.g., land, minerals, solar energy). These combine in some generalized function to create the aggregate E_t used in production.

$$E_t = g(e_{1,t}, e_{2,t}, e_{3,t}) \tag{3}$$

Steady-state solutions (denoted by $\bar{x}$) to this problem impose a few requirements that we leverage to generate the simplified fixed factor aggregate representation in Equation 1. First, $\bar{e}_1 = 0$. Exhaustible and non-renewable (henceforth: non-renewable) resources cannot be used in perpetuity by definition, and so cannot be part of a steady-state solution.[3] Second, $\bar{e}_2$ must be a level that is equal to a potential regeneration rate of that resource. If we withdraw 100 trees from a forest annually, there must exist a forest size that generates 100 new trees annually.[4] $\bar{e}_3$ can be any value up to what exists in nature. There is some total amount of lithium on the planet that can be embodied within products at any given time, and that amount is not reduced by its use.[5] This produces the following relationship.

$$\bar{E} = g(0, \bar{e}_2, \bar{e}_3) \tag{4}$$

Notice that this formulation does not depend on the population size. Population has no independent effect on regeneration rates. Constraints imposed by nature are aggregate, not per capita, constraints. Nor does the population size influence whether it would be inefficient to not manage renewable resources at the level that maximizes what can be withdrawn. Both large and small populations face the challenge that their contemporaneous income is increasing in withdrawal, but dynamic considerations require preservation of resources. Regardless of the size of the population it is imperative to avoid eroding ecosystems to sufficiently low levels.

Furthermore, it is *ex-ante* ambiguous whether larger populations are more likely to pursue an unsustainable path. On one hand, there are more people which makes coordination more difficult, other things equal (and perhaps raises the marginal utility per capita of defecting because per capita

[3] Later we discuss how a model with exponentially decaying use of non-renewable resources changes the problem.
[4] See Appendix A for an overview of these sorts of problems.
[5] Note that this refers to the stock in use, not the newly mined value in t; in the long-run these minerals will be recycled between products if a higher value application becomes available.

consumption of a given resource will be lower). But there will also be more ideas for institutions and/or technologies that increase the probability of overcoming these coordination problems. Indeed, this is exactly what would be predicted by a model of directed technological change (see e.g., Boserup, 1965; Hassler et al., 2021). A cursory look at some resource management problems suggests this is not implausible. For example, global agricultural land use has *fallen* since 2000 in spite of population growth (FAO, 2022).[6] Along that dimension, at least, we are more sustainable at larger populations; improved agricultural TFP has out-paced pressures to defect from a sustainable solution.[7] The simplification here reflects the uncertainty over the long-run relationship between population, technology, wealth, and sustainability.

Climate change deserves quick mention as an important transitory dynamic omitted by this long-run framing. In complementary work, Kuruc et al. (2023) address this quantitatively using William Nordhaus' DICE model (Nordhaus, 2017). They find that population effects on global warming are small for any realistic change in population trajectories. This is because population is a stock. It takes many decades for population sizes to respond to changes in fertility—by the time these differences can emerge, nearly all of the global warming story will be written and so can be ignored here.

In summary then, the fixed factor framing is both realistic and analytically convenient. The environmental constraint is that as populations grow each worker has less E at her disposal, not that the environment is further eroded. This lowers per worker productivity, holding fixed A, implying lower per capita incomes. Under the constant returns to scale assumption on rival inputs:

$$\frac{Y}{N} = y = AF\Big(1, \frac{\bar{E}}{N}\Big). \tag{5}$$

2.2 The Endogenous Growth Component

The literature on endogenous economic growth provides strong reasons to believe that A is not invariant to population sizes and the level of economic activity, other things equal (Romer, 1990; Kremer, 1993; Howitt, 1999; Galor and Weil, 2000; Jones, 2005; Jones and Romer, 2010; Peters, 2022). Larger populations generate more ideas and/or more product variety. Formally, the law of motion we employ for A takes the form in Equation 2 (reproduced here), closely following the

[6]Global agricultural land use available at: https://www.fao.org/faostat/en/#data.

[7]Other examples include the improved o-zone, local air and water pollution, and falling GHG emissions in sufficiently wealthy countries. Insofar as these are made possible by wealth, technologies, or ideas, endogenous growth theory tells us there will be a channel by which a larger population positively influences our management of resources.

semi-endogenous growth literature. Later we discuss straightforward model extensions.

$$\frac{\dot{A}}{A} = \alpha N^{\lambda} A^{-\beta} - \delta_A$$

Population enters the production function of knowledge directly. This can be thought of as a learning-by-doing process or as a scenario where a constant share of human capital is employed in R&D. The scalar on population, α, mediates the effect of people on knowledge accumulation; this term roughly captures the productivity of people as well as the share of time spent in research-focused activity. The exponent λ allows for intratemporal diminishing returns to research effort; β allows for intertemporal diminishing returns to research effort (i.e., if ideas get harder to find after picking the lowest hanging fruit). The final term, δ_A, represents depreciation of the knowledge stock.

This relaxation to non-zero depreciation is non-standard in the endogenous growth literature.[8] The reason we include it here is that it generates a steady-state (see Section 3). The semi-endogenous growth literature produces the counter-intuitive claim that long-run economic growth is directly proportional long-run population growth (Jones, 1995).[9] The zero population growth case we study is a knife's edge case in this literature—TFP growth rates do in fact go zero in the limit, but the rate of convergence is just slow enough for the level of TFP to be unbounded. However, any arbitrarily small value of δ_A generates an endogenous upper bound, a steady-state level of TFP. Furthermore, there is an analytical solution for this long-run level which allows us to study a problem that would otherwise be an indeterminate long-run comparisons of infinite per capita consumption under any population size.[10]

To conclude this section, the simplest model has two key ingredients, respectively capturing the Malthusian concern that large populations dilute natural resources per person and the endogenous growth insight that an economy with more resources should produce more ideas. These components sit within a general CRS production function, allowing them to interact in the usual Cobb-Douglas setting as well as more generalized functions. How these forces push against one another, and on what parameters this depends, is discussed next.

[8] An exception is Dietz and Stern (2015) which includes TFP depreciation in a climate-economy model.

[9] This turns out only to be true for weakly positive rates of population growth. Jones (2022) shows that for negative population growth the semi-endogenous growth model likewise implies that zero population growth.

[10] Aside from the technical benefits, we think this is in practice a reasonable assumption that deserves more study. If effort spent organizing knowledge (e.g., review articles, librarians, etc) is effort spent preventing depreciation of knowledge, the long-run level implications of shrinking or stabilized populations may be dramatically different than a model without this force.

3 Steady State Results

This section presents the steady state implications of this model. An analytical relationship between long-run per capita income, $\bar{y}$, and population levels, $\bar{N}$, arises. The elasticity of per capita income with respect to population can be calibrated to two empirical moments. The ratio between intra- and inter-period diminishing returns knowledge production, $\frac{\lambda}{\beta}$, governs the positive effect of population increases. The income-share of the fixed-factor determines the negative Malthusian effect. Comparing recent estimates of these terms implies that marginal increases to current population sizes increases long-run per capita incomes, a result robust to variations of the model. Globally, the existence of an income-maximizing population depends on the income share of natural resources getting sufficiently large. Historical trends suggest this income share has not increased as populations have grown, seeming to imply that we are not yet near such an income-maximizing population.

3.1 Main Results: The marginal effect of population on per capita income

The only endogenous dynamic variable in this setting is A; $\bar{E}, \bar{N}$ are exogenous and fixed. Restricting our focus to a stable population, Equation 2 implies a steady-state for A.[11]

$$\bar{A} = \left(\frac{\alpha \bar{N}^{\lambda}}{\delta_A}\right)^{\frac{1}{\beta}} \tag{6}$$

Conceptually, this steady state arises as the knowledge stock becomes so large that to even maintain, organize, and employ it takes all people-hours in this sector.[12] This has obvious parallels to the standard Solow model, but the depreciation costs exist one level up. As the stock of knowledge gets unwieldy, the challenge is making use of existing knowledge, not generating new ideas.

The goal of the current exercise is to determine the sign of the elasticity of y with respect to N. It will help to conceptualize the per-worker production function in the following way.

$$\bar{y}(\bar{N}) = \underbrace{\bar{A}(\bar{N})}_{\text{Eqn. 6}} \times F\left(1, \frac{\bar{E}}{\bar{N}}\right) \tag{7}$$

[11] Set $\dot{A} = 0$, and solve for A.

[12] This could be due to the sheer breadth of knowledge society acquires or the increased domain-expertise necessary to even contribute to organizing and preserving knowledge.

Then, the elasticity is

$$
\begin{aligned}
\frac{\partial ln(\bar{y})}{\partial ln(\bar{N})} =& \frac{\partial ln(\bar{A})}{\partial ln(\bar{N})} + \frac{\partial ln(F)}{\partial ln(\bar{N})} \\
=& \frac{\lambda}{\beta} - \underbrace{\frac{\partial F/\partial(\bar{E}/\bar{N}) \times \bar{E}/\bar{N}}{F(1, \bar{E}/\bar{N})}}_{\text{Share of } Y \text{ paid to } E}.
\end{aligned} \tag{8}
$$

The positive term represents how much more knowledge can be accumulated and productively used in the steady-state of this economy from a 1% increase in $\bar{N}$. This is governed by the ratio of the intra-period diminishing returns to research effort, λ, and the degree to which knowledge becomes more difficult to accumulate as A increases, β. Recent work by Bloom et al. (2020) directly targets this parameter and estimates that $\frac{\lambda}{\beta} \in (0.2, 0.5)$ for the aggregate economy. Related analyses generalizing the analytical assumptions of Bloom et al. (2020) imply lower values of β, and hence larger values for $\frac{\lambda}{\beta}$ (Ekerdt and Wu, 2023). Peters (2022) leverages quasi-random population assignments after World War II and estimates a closely related term to be about 0.5.

The negative term represents—holding A fixed—by how much per-worker productivity falls from a 1% increase in $\bar{N}$. This is the Malthusian channel. This sub-elasticity is exactly equal to the income share of natural resources in competitive markets, a result anticipated in a constant elasticity of substitution framework by Weil and Wilde (2009). We denote this term ϕ_E.

Figure 1 documents the time-series of this factor share. It has roughly fluctuated between 2% and 8% over the past half century. The measure plotted is a composite of sources compiled by the World Bank and United States Department of Agriculture on the rents earned by natural resources.[13] We follow the World Bank's *Changing Wealth of Nations* classification and include subsoil energy and minerals, timber resources and all agricultural land as economically valuable natural resources.[14] Estimates of the factor share of agricultural land (in agricultural production) are between 20-30%, which are consistent with historical approximations of about $\frac{1}{3}$ for land's factor share in agriculturally based societies (Wilde, 2017). However, agricultural output is now a small share of global production, partially giving rise to the small estimates in Figure 1.

Another reason for these low values is that we omit urban land from "land's" share of GDP. Urban land values are clearly tied to man-made structures and the people living on or near it. Put

[13]The USDA produces these estimates from the United Nation's Food and Agricultural Organization, so it is global in scope.

[14]This classification misses water resources (and fish, due to the international nature of fish stocks), but these are certainly not large enough to increase the 2-8% resource rents to the 20+% that would be necessary for these resource rents to match the knowledge-elasticity.

differently, humanity could choose to make more urban land, so it is fundamentally not a fixed factor.[15] It would be a mistake to use the high value commanded by urban land as a reflection of natural resources becoming scarce. If anything, this seems to be evidence for a desire (directly or indirectly) to have *more* nearby people.

Returning to Equation 8, estimates for the respective terms are then (0.2,0.5) for $\frac{\lambda}{\beta}$ and (-0.1,-0.02) for ϕ_E. Malthusian-elasticity. This implies an on-net elasticity between population sizes and per capita income somewhere between (0.1,0.5). There are reasons estimates of these respective parameters should come with uncertainty. Natural resources are particularly difficult to measure. But for this quantity to exceed the productivity elasticity, it would need to be the case that global data understates their importance between 3-10-fold, depending on the true value of $\frac{\lambda}{\beta}$.

More important than the quantitative takeaway is the qualitative finding that the relationship we study very likely has a (locally) positive relationship if the forces we capture are the dominant considerations. What is less clear is whether we should expect this relationship to hold if populations grow and natural resources become a more binding constraint on growth. We turn to this question next before discussing extensions of the simple model.

3.2 Income-Maximizing Population

Beyond the local relationship, we can use the steady-state structure in this paper to examine the global relationship between populations and per capita incomes. In particular, we may be able to say something about how close we are to a local max of the relationship $\bar{y}(\bar{N})$, or whether we should expect one to exist. For example, when discussing this topic without a formal model, Greaves (2022) stipulates that there must be an inverted-U relationship between populations and per capita well-being. At small populations, the gains from non-rival benefits we endow on one another exceed any crowding effects, but at sufficiently large populations the opposite must be true. This is a reasonable *a priori* view and one that is consistent with standard environmental worries.

To formalize such an intuition, consider an $F(.,.)$ that has a constant elasticity of substitution between natural and man-made inputs as in Equations 9, 10.

$$Y = A\Big[aN^\rho + (1-a)E^\rho\Big]^{\frac{1}{\rho}} \tag{9}$$

[15] If the resources necessary to build cities were becoming scarce that would of course matter. But this is already reflected in non-urban land prices, mineral rents, and to some extent timber values that are captured in our methodology.

This delivers the following function form for $\bar{y}(\bar{N})$:

$$\bar{y}(\bar{N}) = \Big(\frac{\alpha \bar{N}^{\lambda}}{\delta_A}\Big)^{\frac{1}{\beta}} \Big[a + (1-a)\Big(\frac{E}{N}\Big)^{\rho}\Big]^{\frac{1}{\rho}}. \tag{10}$$

There are three qualitative cases: Cobb-Douglas ($\rho \to 1$), gross substitutes ($\rho > 1$), and gross complements ($\rho < 1$). Figure 2 traces out the general shape of this relationship under these different cases.

The only case here under which the environmentalists concerns are ever borne out is $\rho < 1$, the case of gross complements. It is easiest to see this by understanding why this intuition breaks down in the Cobb-Douglas case. The local elasticity is governed by the population-productivity elasticity less the income share of natural resources, $\frac{\lambda}{\beta} - \phi_E$. In the functional form employed the population-productivity elasticity is fixed; under Cobb-Douglas the income-share of natural resources is also fixed. Therefore, if the difference between them is *ever* positive, it is *always* positive. It is only in the case of gross complements that the income share of natural resources increases as its input share declines.

If we assume that the complements case is the relevant one, the results in Section 3.1 indicate we are still on the left hand side of such a relationship. Determining when the peak would be reached requires estimating when the income-share of natural resources grows to about 0.3, Bloom et al. (2020)'s central estimate for $\frac{\lambda}{\beta}$. Interestingly, Figure 1 does not have any noticeable trend. Since 1970 the population has grown from around 3 to 8 billion, and yet the natural resource share of income has, if anything, fallen. This qualitative fact of a non-increasing trend is not specific to our data construction. It is conventional wisdom that the natural resource (namely, land's) income-share is much higher in times and places where land made (makes) up a larger share of total inputs. Wilde (2017) documents this in the historical case of pre-industrial England; Weil and Wilde (2009) and Monge-Naranjo et al. (2019) document in the cross-section that countries with lower levels of human and physical capital pay a higher share of income to natural resources. These facts makes us doubt that the case of complements is relevant over the range of observed population sizes, and therefore doubt that a sharp increase in the share of income going to natural resources at nearby population sizes is unlikely.

3.3 Model Extensions

There are a few dimensions along which we can relax the previous assumptions on both the productivity and environmental sides of the model, but retain much of the simplicity. These alternative formulations provide the same takeaways.

3.3.1 Factor-augmenting technological change

A more realistic version of this model might have factor-augmented technological change. For example, endogenous directed technological change (e.g., Boserup, 1965; Acemoglu et al., 2012) may be an important mechanism for pinning down the quantitative elasticities. Indeed, in a series of recent papers Hassler et al. (2021, 2023) argue that this is a necessary mechanism to explain patterns related to fossil fuel use. In particular, Hassler et al. (2021) demonstrate that high levels of complementarity over short time horizons can be consistent with a flat long-run factor shares if technological change is E-augmenting (whether exogenously or endogenously). In some sense, we have omitted this possibility for conservatism: the main results demonstrate that *even without* directing technological change towards increasingly tight resource constraints, the marginal relationship between population and per capita income is positive. However, it is straightforward to generalize our main finding to an arbitrary degree of factor-augmenting technological improvements, including non-directed N-augmenting improvements.

Start by denoting the production function as follows.

$$\begin{aligned} &Y = F(A_N N, A_E E) \Rightarrow \\ &y = F\Big(A_N, A_E \frac{E}{N}\Big) \\ &y = A_N F\Big(1, a_e \frac{E}{N}\Big), \;\; \text{where } \; a_e \equiv \frac{A_E}{A_N} \end{aligned} \tag{11}$$

Then, the corresponding elasticity between population and per capita income becomes the following, where again ϕ_E equals the share of income going to the fixed factor.

$$\frac{\partial ln(\bar{y})}{\partial ln(\bar{N})} = \frac{\partial ln(\bar{A}_N)}{\partial ln(\bar{N})} - \Big(1 - \frac{\partial ln(a_E)}{\partial ln(\bar{N})}\Big)\phi_E \tag{12}$$

The relationship is intuitive and informative. If the elasticity of a_E with respect to N is one, then it's as if there has been no change in the fixed factor. Increasing N by 1% decreases $\frac{E}{N}$ by 1% (by construction), but increases a_E by 1% (by assumption), leaving the product of these terms unchanged. In the case of Hick-neutral technological change, a_E is fixed and this collapses to the baseline case.

In the case where technological progress is human and physical capital augmenting, a_E will in general decrease, compounding the losses from $\frac{E}{N}$ decreasing. However, there is a limit on how severe this decrease in a_E can be. This fraction can only decrease in proportion to the increase in A_N. Formally, $\frac{\partial ln(a_E)}{\partial ln(\bar{N})} \geq -\frac{\partial ln(\bar{A}_N)}{\partial ln(\bar{N})}$. In this extreme case where *all* technological progress is N-augmenting, we can write the net-elasticity as:

$$\frac{\partial ln(\bar{y})}{\partial ln(\bar{N})} = (1-\phi_E)\frac{\partial ln(\bar{A}_N)}{\partial ln(\bar{N})} - \phi_E \tag{13}$$

The productivity-elasticity is now mitigated by ϕ_E% before being weighed against ϕ_E. Using the baseline values for these parameters this will not be quantitatively meaningful. Rather than comparing roughly 0.3 to 0.03, we would be comparing 0.27 to 0.03. In short, variants of factor-augmenting technical change can not themselves overturn the results, even under the most pessimistic version of this assumption.

3.3.2 Exhaustible resources

Some observers are worried about the stock of exhaustible resources rather than the long-run withdrawal of renewable resources. Fossil fuels are foremost among these concerns. Exhaustible resources amount to a classic "cake-eating" problem where we can denote the initial stock as $\mathbb{E}$. For analytical simplicity, and consistent with the flat trend in factor shares here and in Hassler et al. (2021), assume a Cobb-Douglas specification for this exercise.

$$\max \sum_{t=0}^{\infty} \delta^t \frac{1}{1-\sigma} y_t^{1-\sigma} \tag{14}$$

$$\text{with } \; y_t = A_t \Big(\frac{E_t}{\bar{N}}\Big)^{1-a} \tag{15}$$

$$\text{and } \; \sum_{t=0}^{\infty} E_t = \mathbb{E} \tag{16}$$

Here the discount rate is denoted δ, which now matters as we are focused on environments without a steady state level of consumption to analyze. We have already established that $A \rightarrow \left(\frac{\alpha \bar{N}^{\lambda}}{\delta_A}\right)^{\frac{1}{\beta}}$ independent of the environmental side of the model. For simplicity then assume A reaches this level reasonably quickly and is therefore fixed for the long-run study of this model. With a fixed

A, N it can be easily shown that the solution is characterized by $\frac{E_t}{E_{t+1}} = \delta^{\frac{1}{1+\sigma a - a}}$.

The level of environmental withdrawals remains independent of the population size. Therefore, it also remains true that the trade-off of a larger population is a $\frac{\lambda}{\beta}\%$ increase in A at the expense of a 1% lower $\frac{E_t}{N}$. The only difference is that the trade-off is period-by-period and the use of E falls each period. However, in this Cobb-Douglas specification a 1% decline in $\frac{E_t}{N}$ reduces y_t by $(1-a)\%$ regardless of the level of E being drawn. The difference in this setting—that $\frac{E}{N}$ is declining each period—turns out to be unimportant for comparing a 1% loss in $\frac{E}{N}$ to a $\frac{\lambda}{\beta}\%$ increase in A.

3.3.3 Non-rival benefits from natural resources

Alongside the rival ecosystem services that earn profits—and are conceptually captured in our income-share terms—there may also be non-rival benefits of nature that increase with its stock. Consider a generalized production function building from Dasgupta (2021).[16]

$$Y = AB^{\xi}F(N, \bar{E}) \tag{17}$$

Here B captures the general health (or stock) of the nature, what Dasgupta (2021) calls the biosphere. It performs regenerative services—such as filtering H_20 throughout the water cycle—and helps promote innovation and learning—such as plants in the Amazon that provide the ideas for new pharmaceuticals. If you take a broader view of Y beyond measured GDP, you might also consider B to contribute to Y via non-use values; we all derive some intellectual value from the mere existence of bio- and scenic-diversity.

What we have called E throughout the paper is the flow of ecosystem services being drawn from B. Previously the stock of B was only indirectly useful (in that it determines how much E can be drawn) and so was left undiscussed. These non-rival benefits introduce a channel by which the stock itself is directly beneficial. This indirect channel changes the optimal level of E as the flow of E will determine the level of B (see Appendix 2.1). Previously, it would have been optimal to erode the biosphere until it reached its peak growth rate.[17] When B enters directly we have a competing incentive to keep B larger than where it reaches its regenerative peak.

We reiterate here that this coordination problem is difficult to solve, regardless of population

[16] See Dasgupta (2021) Chapter 4*.

[17] For example, in an ocean with fish populations at their carrying capacity, there is no net-regeneration since populations cannot grow. Doing some fishing that reduces the stock in fact increases the rate of growth, and hence what can be drawn in a steady state.

sizes, and is not the problem that focused on here. If it is true that our ecosystem withdrawals are not optimal, that problem needs to be solved by means other than population reduction. Even smaller populations than our own will need to figure out how to coordinate away from over use.

4 Conclusion

The human population is projected to stop growing—and perhaps begin shrinking—during the lifetime of children alive today. Whether it would be better to stabilize at higher population sizes depends on many things: transition dynamics, non-market goods, whether there is value in existence itself as in e.g., Klenow et al. (2023), etc. An issue of obvious importance will be whether per capita consumption will be enduringly influenced.

This paper demonstrates that straightforward modifications and calibrations of the existing models that capture the most discussed competing forces—sharing of fixed natural resources and innovation gains of larger populations—suggest the relationship between population size and per capita outcomes is a positive one. This appears true locally and is not at risk of being overturned at nearby population levels. Furthermore, more complicated extensions to factor-augmented technological progress or alternative modeling of environmental services strengthen the case for on-net increasing returns to scale. Insofar as technological progress and fixed resources are the primary forces that determine the sign of total scale effects, there is little reason to believe a world population that stabilizes at 7 billion will be richer per capita than a world that stabilizes at 8 billion.

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous (2012) "The environment and directed technical change," *American Economic Review*, 102 (1), 131–166.

Bloom, Nicholas, Charles I Jones, John Van Reenen, and Michael Webb (2020) "Are Ideas Getting Harder to Find?" *American Economic Review*, 110 (4), 1104–44.

Boserup, Esther (1965) *The conditions of agricultural growth: the economics of agrarian change under population pressure*: London: Allen & Unwin.

Córdoba, Juan Carlos and Xiying Liu (2022) "Malthusian Stagnation is Efficient," *Theoretical Economics*, 17, 415–460.

Córdoba, Juan Carlos, Xiying Liu, and Marla Ripoll (2022) "Optimal Population on a Finite Planet," *Working Paper*.

Dasgupta, Partha (2019) *Birth and Death: Arrow Lecture*, 1–120: Columbia University Press, http://www.jstor.org/stable/10.7312/dasg16012.7.

——— (2021) *The Economics of Biodiversity: The Dasgupta Review*: London: HM Treasury.

Desmet, Klaus, Dávid Krisztián Nagy, and Esteban Rossi-Hansberg (2018) "The geography of development," *Journal of Political Economy*, 126 (3), 903–983.

Dietz, Simon and Nicholas Stern (2015) "Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions," *The Economic Journal*, 125 (583), 574–620.

Ekerdt, Lorenz and Kai-Jie Wu (2023) "Self-Selection and the Diminishing Returns to Research," *Working Paper*, Available at https://sites.google.com/view/lorenz-ekerdt/research.

FAO (2022) "FAOSTAT,"Technical report, United Nations, Retreived from: https://www.fao.org/faostat/en/#data on Dec. 14, 2022.

Galor, Oded (2011) *Unified Growth Theory*: Princeton University Press.

Galor, Oded and David N Weil (2000) “Population, Technology, and Growth: From Malthusian Stagnation to the Demographic Transition and Beyond,” *American Economic Review*, 90 (4), 806–828.

Greaves, Hilary (2022) “Optimum Population Size,” in Arrenhius, G., K. Bykvist, and T Campbell eds. *Oxford Handbook of Population Ethics*: Oxford University Press.

Gross, Till and Paul Klein (2023) “Innovation Driven Growth in a Multi-Country World,” *Working Paper*, Available at: https://sites.google.com/site/tillgrosshomepage/.

Hassler, John, Per Krusell, and Conny Olovsson (2021) “Directed Technical Change as a Response to Natural Resource Scarcity,” *Journal of Political Economy*, 129 (11), 3039–3072.

——— (2023) “Finite Resources and the World Economy,” *Journal of International Economics*.

Howitt, Peter (1999) “Steady endogenous growth with population and R. & D. inputs growing,” *Journal of Political Economy*, 107 (4), 715–730.

Jones, Charles I (1995) “R&D-Based Models of Economics Growth,” *Journal of Political Economy*, 103 (4).

——— (2001) “Was an Industrial Revolution Inevitable? Economic Growth Over the Very Long Run,” *The B.E. Journal of Macroeconomics*, 1 (2).

——— (2005) “Growth and Ideas,” in Aghion, Philippe and Steven N Durlauf eds. *Handbook of Economic Growth*, 1B, 1063–1111: Elsevier.

——— (2022) “The End of Economic Growth? Unintended Consequences of a Declining Population,” *American Economic Review*, 112 (11), 3489–3527.

Jones, Charles I and Paul M Romer (2010) “The New Kaldor Facts: Ideas, Institutions, Population, and Human Capital,” *American Economic Journal: Macroeconomics*, 2 (1), 224–45.

Klenow, Peter, Charles I Jones, Mark Bils, and Mohamad Adhami (2023) “Population and Welfare: The Greatest Good for the Greatest Number,” Available at: http://web.stanford.edu/~chadj/popwelfare.pdf.

Kremer, Michael (1993) “Population Growth and Technological Change: One Million B.C. to 1990,” *The Quarterly Journal of Economics*, 108 (3), 681–716.

Kuruc, Kevin, Sangita Vyas, Mark Budolfson, Mark Geruso, and Dean Spears (2023) "A Larger World Population Increases Average Living Standards, Net of Climate Damages," *Population Wellbeing Initiative Working Paper*, Available at: https://sites.utexas.edu/pwi/files/2023/01/Stabilization_Climate.pdf.

Monge-Naranjo, Alexander, Juan M Sánchez, and Raül Santaeulalia-Llopis (2019) "Natural Resources and Global Misallocation," *American Economic Journal: Macroeconomics*, 11 (2), 79–126.

Nordhaus, William D (2017) "Revisiting the social cost of carbon," *Proceedings of the National Academy of Sciences*, 114 (7), 1518–1523.

Peretto, Pietro F and Simone Valente (2015) "Growth on a finite planet: resources, technology and population in the long run," *Journal of Economic Growth*, 20 (3), 305–331.

Peters, Michael (2022) "Market Size and Spatial Growth – Evidence from Germany's Post-War Population Expulsions," *Econometrica*, 90 (5), 2357–2396.

Peters, Michael and Peters Walsh (2021) "Population Growth and Firm Dynamics," *National Bureau of Economic Research Working Paper*, No. 29424.

Pindyck, Robert S (2022) "Population, Productivity, and Sustainable Consumption," *NBER Working Paper*, No. 30019.

Romer, Paul M (1990) "Endogenous Technological Change," *Journal of Political Economy*, 98 (5, Part 2), S71–S102.

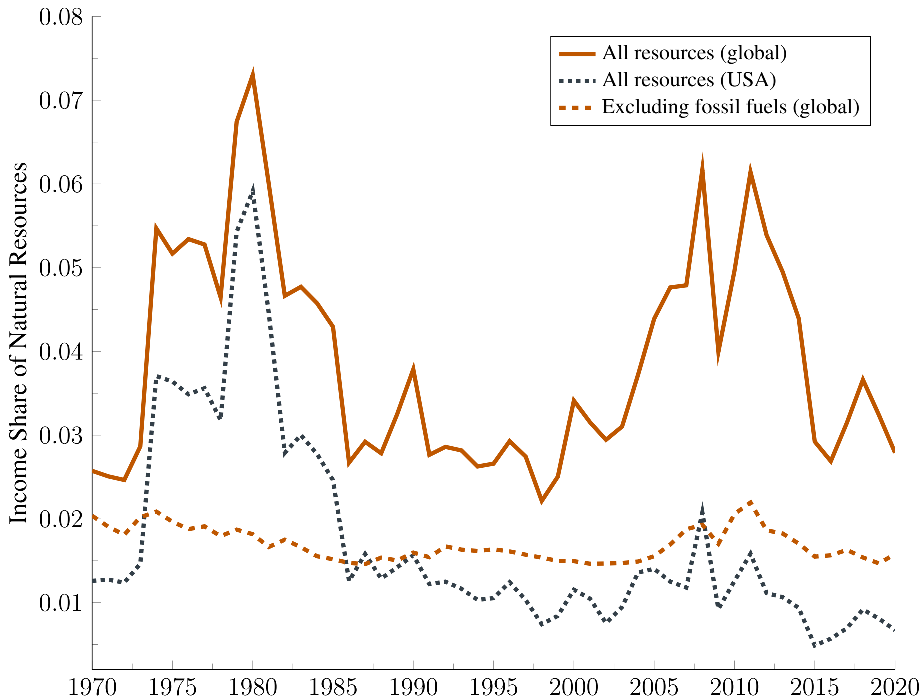
Vollrath, Dietrich (2012) "Land tenure, population, and long-run growth," *Journal of Population Economics*, 25, 833–852.

Weil, David N and Joshua Wilde (2009) "How Relevant is Malthus for Economic Development Today?" *American Economic Review: Papers & Proceedings*, 99 (2), 255–60.

Wilde, Joshua (2017) "How substitutable are fixed factors in production? Evidence from pre-industrial England," *Working Paper*, Available at: https://www.usf.edu/arts-sciences/departments/economics/documents/substitutability_1.pdf.

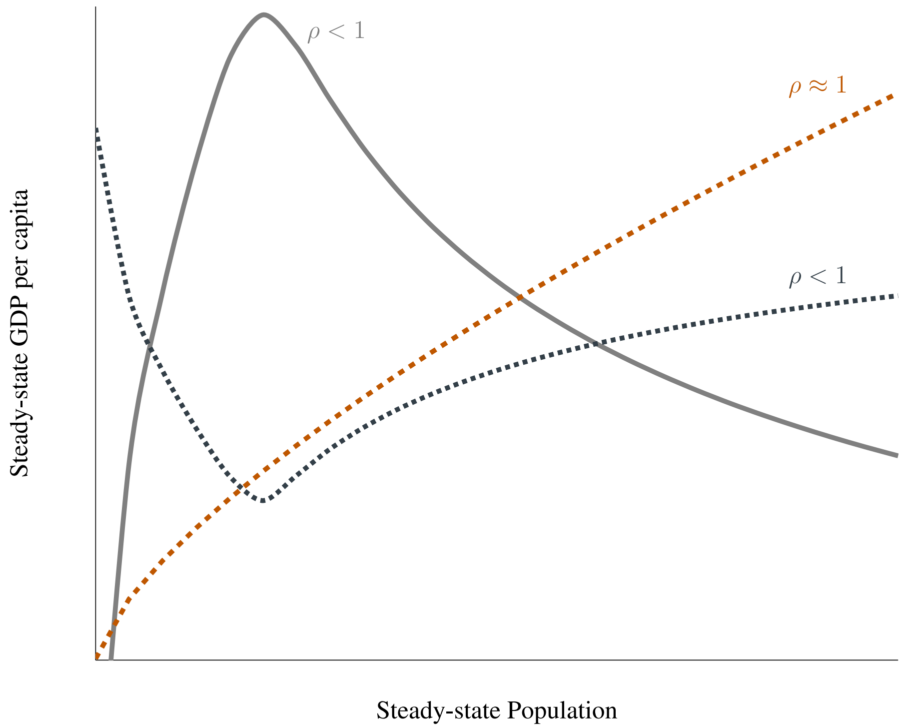
Figures

Figure 1: Natural resource shares are small and non-increasing



Notes: Share of income paid to natural resources over time. (Solid) Global income share paid to all natural resources, following World Bank classification to include: (a) subsoil energy and minerals; (b) timber resources; (c) crop land; (d) pasture land. Details of each category are contained in the Appendix. (Dashed) This same income share, but using only US data to ensure trend or level not driven by unreliable global data. (Dashed) Excludes fossil fuels which drive the level and volatility of this series, but not its flat trend.

Figure 2: Illustrative examples of CES relationships between N, E



Notes: Different shapes of the relationship between per capita incomes and population sizes based on a CES production function of the form. Specifically, where $\bar{y}(\bar{N}) = \left(\frac{\alpha \bar{N}^{\lambda}}{\delta_A}\right)^{\frac{1}{\beta}} \left[a + (1-a)\left(\frac{E}{N}\right)^{\rho}\right]^{\frac{1}{\rho}}$ with $\frac{\lambda}{\beta} > (1-a)$. Only in the case of complements ($\rho < 1$) are environmental concerns dominant at large populations.

Appendix

A Details of renewable resource problem

As noted in the main text, Dasgupta (2021) argues that the entire biosphere, B, can be roughly conceptualized as renewable resource problem. If nature is undisturbed by human activity, most resources will regenerate.

Steady-state solutions to such problems are characterized by withdrawals of constant ecosystem services, $\bar{E}$, exactly equal to the amount of regeneration the renewable resource produces (which will be a function of its stock). Formally, assume that the biosphere has a regeneration function, $R(B)$, as in Equation A1, taken from Dasgupta (2021).

$$R(B) = rB\left[1 - \frac{B}{K}\right]\left[\frac{B-T}{K}\right] \tag{A1}$$

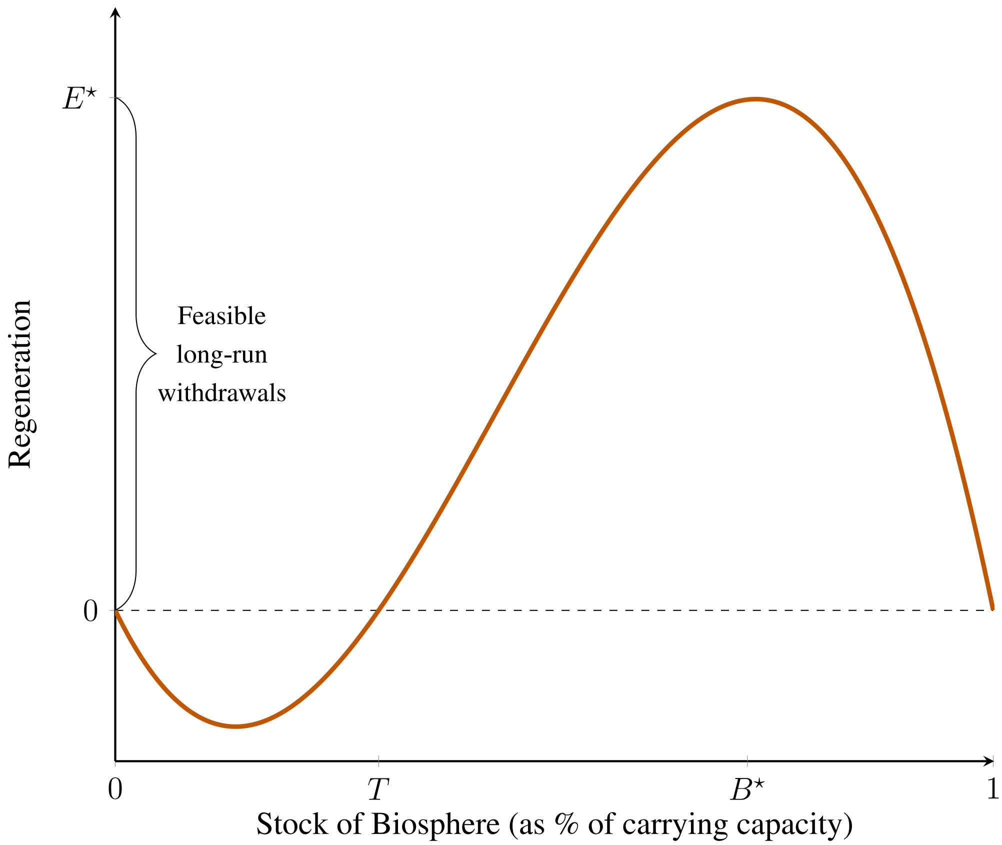
B is the stock of biosphere as it relates to human production/consumption and $R(B)$ is the amount of regeneration. K is the carrying capacity on this renewable resource—where the natural world would converge with minimal human interference. T is a “tipping point”—should we degrade the environment below T, regeneration becomes negative and the system collapses towards $B = 0$. r is the rate of regeneration in the absence of a tipping point or carrying capacity. The law of motion on B is then governed by the difference between regeneration, $R(B)$, and the amount of ecosystem services drawn for human production/consumption, E.

$$\dot{B}(B) = R(B) - E \tag{A2}$$

In a steady-state solution $\bar{E} = R(\bar{B})$. Notice that any level of $B > T$ can be consistent with a steady-state outcome. According to Equation A2, the steady-state level of B pins down the level of $\bar{E}$. In this model, there is a unique $B^{\star}$ that optimizes the regeneration rate and hence the value of $\bar{E}$.[18] Income is increasing in E, so the optimal solution in the baseline model is to manage B such that the peak of regeneration is reached. In the model of Section 3.3.3, there is an additional benefit from a higher level of B. Generally, this will increase $B^{\star}$ beyond the level that maximizes only E.

[18]Notice that it is *not* the maximal B. Once B is at it's carrying capacity there is not net growth to drawn down, by definition.

Figure A1: Regeneration rate with tipping point



Nothing about this solution depends on the population size. The population size has no effect on regeneration rates, conditional on E, and it would be similarly inefficient for any population size to not manage B at the level that maximizes $R(B)$. Large and small populations alike face the challenge of intertemporal externalities. We abstract from the underlying details of this resource management problem and import a steady state solution, $\bar{E}$, of this independent subproblem into the aggregate production function.

B Data Appendix

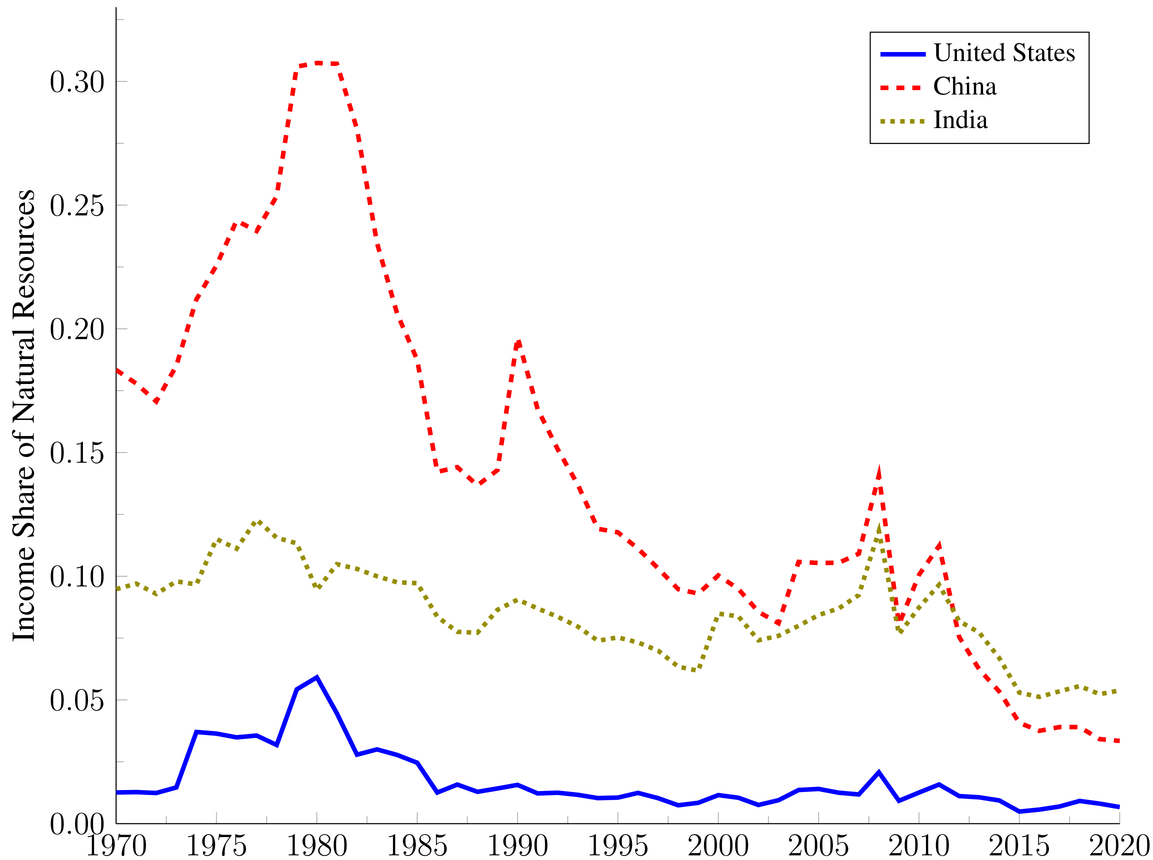
There exists public estimates on natural resource shares from reputable sources (namely, the World Bank and the US Department of Agriculture). This leaves us only with the task of aggregating existing estimates. Figures on rents as a percent of GDP for timber/forests, minerals, coal, oil, and natural gas come from the "Adjusted Net Savings" dataset (updated 9/23/2022) from the World Bank's 2021 "Changing Wealth of Nations" report. These figures are provided on an annual basis and beginning in 1970. The dataset has missing years at the country-level but makes estimates at the global level in each year.

To determine the rents paid to agricultural land—inclusive of both crop and pasture applications—three data series are employed. First, FAOSTAT's "Value of Agricultural Production" (updated 11/15/2022) provides the total value of agricultural output in units of "Gross Production Value (constant 2014-2016 thousand US$)". We drop all animal products from the dataset except for cattle, sheep and goat products because the cost share due to land rents for animal products other than these 3 are small enough to be justifiably ignored. We then sum the total value of agricultural output for each country and at the global level.

Second, we need the share of total agricultural cost that is paid to agricultural land in each country and at the global level. The USDA's "International Agricultural Productivity" (updated 10/7/2022) can be leveraged here. Estimates of factor shares within agricultural production are provided for every decade from 1961-2020. Total agricultural revenues equal total agricultural costs inclusive of implicit land and capital rents. Therefore we can multiply the decadal factor shares for land by total annual agricultural revenue to get the total rents paid to agricultural land in each location-year.

Finally, we use the World Bank's GDP dataset (updated in constant 2015 US$ to be in the same units as agricultural land rents). We divide agricultural land rents by GDP to get the percent of GDP paid to all agricultural land. We then simply combine the World Bank rent estimates for timber and subsoil minerals with the agricultural land rents to get the total percent of GDP paid to the recorded natural resources.

Figure A2: Different countries have similar long-run trend



Notes: Income share of resources by country. Both across and within countries levels of economic development (e.g., human and physical capital accumulation) the share of income going to natural resources shrinks. This suggests natural resources have been complements over the domain of economic development observed through 2020.