The Economics of Biodiversity: Afterword

Partha Dasgupta[1]

Abstract

This Afterword to *The Economics of Biodiversity: The Dasgupta Review* discusses (i) the ideas in the *Review* that have been accepted readily by decision makers and are being put into operation, (ii) those that have been accepted but are judged by decision makers to be unworkable in the contemporary climate, (iii) those that are seen as politically too sensitive even to acknowledge in public.

Keywords Biosphere · Impact inequality · Population · Inclusive wealth · Biodiversity

1 Background

In Spring 2019 the UK's then Chancellor of the Exchequer Philip (now Lord) Hammond invited me to prepare an independent, global review of the economics of biodiversity. The report (henceforth, *Review*) was completed in mid-December 2020. The full text is 601 pages long, but because it necessarily contains much technical material, I prepared an abridged (99 pages), non-technical version, and my Treasury team prepared a brief, collating the *Review*'s headline messages. All three documents are available online on the UK Treasury's website; but the full *Review*, with several additional sections, boxes, and annexes to include themes of potential interest to graduate students is also being published by Cambridge University Press later this year.

Because both my team and I felt we needed a break on completion, the *Review* was launched before the public only on 2nd February 2021, at the Royal Society, London (the launch proceedings are available on you-tube). Soon thereafter the Treasury issued a response to the *Review* (also available on its website) and demonstrated its support by retaining several members of my team for the remainder of the calendar year to facilitate its dissemination. I am grateful to the Treasury for their courtesy, for I have learnt an enormous

✉ Partha Dasgupta
    pd10000@cam.ac.uk

[1] Faculty of Economics, University of Cambridge, Cambridge, UK

amount from the more than 150 events I have since been involved in (lectures, Q&As, interviews, and panel discussions), engaging not only with professionals from environmental and development charities, government departments, international organizations, scientific associations, think tanks, academic journals, literary magazines, research institutes, business schools, and groups representing indigenous people; but numerically even more, with financiers, bankers, farmers, ecologists, legal scholars, politicians, environmentalists, agronomists, statisticians, journalists, clerics, Earth scientists, and national and international civil servants. There has no doubt been self-selection at work, but the level of interest in the economics of Nature among people at large feels unreal to me when I place it in comparison to the interest among editorial boards of leading economics journals. Which is why, I am most grateful to Professor Ingmar Schumacher, who as editor of this symposium, encouraged me to put down my impressions of how the *Review* has been received; in particular, identify (i) the ideas that have been accepted readily and are being put into operation, (ii) those that have been accepted but are judged by decision makers to be unworkable in the contemporary climate, (iii) those that are seen as politically too sensitive even to acknowledge in public. I do that, respectively, in Sects. 4, 5, and 6. Again, with Schumacher's encouragement and that of a referee, I use Sect.7 to reflect on a New Consensus that appears to have formed among national and international decision makers on global economic development.

And I am grateful to Professors Heidi Albers, Amy Ando, Ed Barbier, and Scott Barrett for their contributions to this symposium. Their pieces stand on their own and extend the *Review*'s reach. [1]

2 Motivation

That economic policies should be evidence-based is (or should be) an incontrovertible requirement, but it is of no use if the evidence is obtained from a misleading conception of the human condition; for faulty models produce spurious evidence. Systems of thought that do not acknowledge humanity's embeddedness in Nature when used to project present and future possibilities open to us mislead. The findings of ecologists and Earth scientists have increasingly demonstrated that such systems of thought mislead so hugely that policies based on them not only endanger future generations, but also damage the lives of the world's contemporary poor.

The global standard of living has improved enormously since the end of World War II. Per capita global income has increased nearly 5-fold to some 16,000 dollars PPP annually, life expectancy at birth has increased from 46 years to 72 years, and the proportion of people in extreme poverty has declined from approximately 60–10%. But these statistics should be tempered by the thought that prominent Earth scientists see 1950 as the year we entered the Anthropocene (Voosen, 2016). Since then, expansion in our demands for Nature's *provisioning goods* (food, water, timber, fibers, pharmaceuticals, non-living materials – that is, the ingredients that, with human effort, go to shape the final products reflected in GDP) has eaten into Nature's ability to supply *maintenance and regulating services*, among which are carbon sequestration, nutrient recycling, decomposition of waste, pollination, nitrogen

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[1] A previous version of this Afterword was the basis of my David Pearce Lecture at the annual conference of the European Association of Environmental and Resource Economists, held in Rimini in June 2022.

fixing, soil regeneration, purification of water, and maintenance of the biosphere's gaseous composition. [2]

There is a tension between the global demand for the biosphere's provisioning goods and our need for maintenance and regulating services. When we engage in mining, quarrying, and more broadly in the land-use changes accompanying expansions of crop agriculture, animal farming, plantations, and construction, that tension is felt.

The processes that furnish us with maintenance and regulating services are for the most part silent and invisible (think of the things that are happening deep in the soils or the ocean depths). Ecologists and Earth scientists trace the efficacy with which those processes are functioning and have functioned in the past from their visible signatures (Waters et al., 2016). Which is why the significance of these services continues to be underestimated by decision makers. But maintenance and regulating services are the foundation on which we exist. They are *primary*, akin to "basic industries" in the standard classification of industrial production sectors.

There is a further sobering fact. Although technological advancements have repeatedly shown ways to substitute provisioning goods among one another (fossil fuels replacing timber, solar panels substituting for fossil fuels in energy production, and so on), Nature's maintenance and regulating services are *complementary* to one another: disrupting one sufficiently disrupts the others. The mutual influence of climate change and destruction of the world's tropical rainforests is an example. Thus, the long-standing question whether natural resources can be substituted for in production by labor and produced capital pertains to provisioning goods (Dasgupta and Heal, 1979), not to maintenance and regulating services. Complementarities among the latter tell us that we are embedded in Nature, we are not external creatures. The biosphere is not exactly a house of cards, but we humans are now so ingenuous that we would be able to reduce it to one if we put our mind to it.

For many years I have felt that even though the literature on environmental and resource economics has repeatedly exposed the harm done by the practice in contemporary economics of detaching the human economy from the biosphere, it hasn't done so from top to bottom. I tried to correct that in *The Control of Resources* (Dasgupta, 1982), but I constructed it as a series of short chapters, identifying the dynamics that characterize key ecosystems (fisheries, forests, water bodies, the atmosphere as sinks for pollutants, and so on). Although the monograph served as a template for the *Review*, there was still a need to reconstruct growth and development economics and the economics of poverty in a way that sees we humans as being embedded in Nature, rather than being external to it. I also felt increasingly that if contemporary economics is to be reconstructed, we would have to study our embeddedness in Nature at all levels: from the individual person, through households, communities, nations, regions, to the global economy. The latter is of course the scene where growth and development economics of the long run is fashioned, so the needed reconstruction would also refashion macroeconomic models of the long run. It would read contemporary economic growth as being countered by depreciation of the finite, self-regenerative entity that is the biosphere.

In contrast, mathematical formulations of the economics of climate change have viewed the climate system in isolation from the biosphere's other, complementary systems (Nordhaus, 1994; Nordhaus and Boyer, 2000; Stern, 2006). The models graft an isolated climate

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[2] The *Review* adopts the Common International Classification of Ecosystem Services, which was built on the pioneering work of the Millennium Ecosystem Assessment (MEA, 2005).

system into contemporary models of growth and distribution. And the latter see the human economy as being external to the biosphere, which has of course been their abiding weakness. It is the reason early estimates of the global cost of carbon were so low as to be unbelievable ($10–20 per ton). Dramatic increases in estimates in recent years ($200 and more per ton) are a recognition that, among other happenings, extreme climate events can be expected to occur more frequently with rising carbon concentration in the atmosphere; there is little formal acknowledgment that the processes driving Earth's climate system work in tandem with all its other processes. Chapters4* and 13* of the *Review* contain a prototype of the kind of macroeconomic model of the long run that is now needed. But it is only a prototype. Much work remains to be done, extending its coverage, and estimating the parameters of such a model.

The *Review*'s conceptual frame was developed in a series of articles I had co-authored over the years – in pretty-nearly every combination of authorships - with Kenneth Arrow, Scott Barrett, Aisha Dasgupta, Paul Ehrlich, Lawrence Goulder, Simon Levin, and Karl-Goran Mäler. The papers were published in a variety of journals, including *Environmental and Resource Economics*, *Environment and Development Economics*, *Economic Theory*, *Journal of Economic Perspectives*, *Science*, *Population and Development Review*, and the *Proceedings of the US National Academy of Sciences*. The *Review* was influenced greatly also by discussions I have had over the years with Peter Raven and by the collection of articles on biological extinctions we invited for a conference at the Vatican, the proceedings of which were published in Dasgupta, Raven, and McIvor, eds. (2019). My debt to my co-authors and to my team at the Treasury is enormous and self-evident to me. In what follows, all references to the *Review* are to its full version.

3 The Impact Inequality

Although the *Review* has "biodiversity" in its title, its focus is on *ecosystems*. Ecosystems are self-regenerative assets but are subject to external influences. Fisheries, forests, wetlands, grasslands, coral reefs, mangroves, the atmosphere, and lakes and seas are prime examples. That the processes driving their dynamics are non-linear is of especial significance, for they harbor tipping points, that is, locations of abrupt changes. Biodiversity is a characteristic of ecosystems. When defined with care – for example, laying stress on functional diversity of ecosystems as opposed to genetic diversity - biodiversity has been found to enhance the ability of ecosystems to supply maintenance and regulating services. It does that by, among other things, increasing the resilience of ecosystems to disturbances. We may think of the biosphere as an all-encompassing ecosystem. The *Review* can thus be read as an application of capital theory, where the biosphere is taken to be an asset in which the human economy is embedded. [3]

3.1 Formulation

We call the gap between the demand humanity makes of maintenance and regulating services and the biosphere's ability to meet that demand on a sustainable basis, the *Impact*

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[3] This is like the proposal in Lovelock (1995), that we should view the Earth system as a self-regulating entity. That the author's name for it, *Gaia*, has been read as having religious overtones is beside the point.

Inequality. To measure the global demand for those services, let global GDP serve as a measure of human activities. It is illuminating to decompose GDP by noting that it is, tautologically, the product of population size and per capita GDP. So, let N be global population and y be per capita global GDP. Global GDP is then Ny. But GDP is the market value of the final goods and services produced in a period (a year), expressed, say, in dollars PPP. We need to relate that to the demand that our activities make on Nature's maintenance and regulating services. Let α be numerical measure of the efficiency with which those services are transformed into marketed final products. It follows that Ny/α is the aggregate demand for Nature's services. Today Ny/α would be called the *global ecological footprint*. Here I am adopting a global perspective; the global ecological footprint is an aggregate of individual footprints. [4]

For expositional ease I assume that Nature's maintenance and regulating services can be aggregated into a numerical measure, which we label by G. We should imagine that the flows of those services are valued at accounting prices, reflecting their social worth, and then summed to give us G. G is the biosphere's *net* regenerative rate.

The biosphere is a stock. We denote it by S. Again, we should imagine that S is the accounting value of the ecosystems that together comprise the biosphere. But G is a function of S. As with fisheries, G is a declining function of S when S is large (G is the *net* regeneration rate, remember), but when S is small, G can be made to increase by allowing S to increase. Because S is bounded, G is bounded.

Armed with this notation, the Impact Inequality (Barrett et al., 2020) can be expressed as.

$$Ny/\alpha > G(S) \tag{1}$$

The size of the inequality is a measure of humanity's ecological overshoot. By some estimates the ratio of our demand for maintenance and regulating services (the left-hand side of inequality (1)) to Nature's ability to meet that demand on a *sustainable* basis (the right-hand side of inequality (1)) is today 1.7, whence the metaphor that we need 1.7 Earths to meet our demands (Wakernagel and Beyers, 2019). The term "sustainable" is an all-important qualifier here, for it says that we are enjoying the overshoot at the expense of the health of the biosphere; that is, by depleting S. The number 1.7 is almost certainly an underestimate, which makes it even more a reason that inequality (1) be converted to an equality sooner rather than later. We are in a fire-fighting situation.

If accounting prices are not available, the Impact Inequality would be a string of inequalities, reflecting the overshoot of various maintenance and regulating services. The idea of planetary boundaries (Rockström et al., 2009; Steffen et al., 2015), nine in number, is cast in the latter language.

3.2 Application: The UN's Sustainable Development Goals

Humanity's ecological overshoot did not find quantitative expression in the design of the UN's Sustainable Development Goals (SDGs). 17 in number, the goals include elimination

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[4] Ehrlich and Holdren (1971) decomposed the global ecological footprint (they called it "impact") in terms of population, income, and technology. Barrett et al. (2020) formalised the latter as the efficiency with which Nature's maintenance and regulating services are converted into final products. Both technology and institutions shape that efficiency.

of poverty and hunger; attainment of good health and well-being, quality education, gender equality, clean water and sanitation, clean energy, decent work and economic growth; and actions that lead to reductions in carbon emissions and improved aquatic life. The goals are meant to be reached by 2030, but the question whether the SDGs, should they be reached, are *themselves* sustainable was not addressed. I have been unable to find an explanation for the oversight. The *Review* (Ch. 4, Box 4.6) offers an exercise showing that if the Impact Inequality is to be converted into an equality by 2030, then under the assumption that global GDP grows at the rate implied in the formulation of the SDGs, α would have to increase between now and then at a percentage rate 4–5 times higher than it has in recent decades. That is as unlikely a happening as I can imagine. Well-intentioned though they are, the SDGs were framed with little attention to the economics of biodiversity.

Other things equal increases in α would reduce the ecological footprint. The received economics of climate change has focused on technological change and pricing carbon emissions as the means for raising α (Nordhaus and Boyer, 2000; Stern, 2006). It comes with the belief that even a moderate annual investment in the transition to clean energy (say, 2% of GDP) can close the gap between carbon emissions and assimilation (i.e., achieve net zero emission) by 2050 and enable the global economy to enjoy growth in GDP indefinitely.

The *Review* reads ecology and the Earth sciences as saying that the above view is a misplaced reading of the biosphere's workings. More particularly, the *Review* argues that because of the complementarities among Nature's services, a reliance on energy pricing and the development of clean energy technologies to overcome our ecological overshoot should be expected to backfire. It argues that we should also be looking for ecological solutions. Raising S and therefore G by allowing Nature to grow is investing in Nature. Such investment does not so much involve machinery and hardware as it involves simply waiting; that is, waiting for Nature to recover. [5] The remaining factors in the Impact Inequality are N and y. Below we study ways to reduce y and curb projected increases in N.

The Impact Inequality is a snapshot of the global socio-ecological system. It is an *accounting* statement on the state of Earth's ecosystems at a moment in time. The inequality contains no information on how the five factors N, y, α, G, S influence one another over time. To identify their mutual influence requires a dynamic model that sees the human economy embedded in Nature. The *Review* contains a dynamic model doing just that (Ch. 4*). But even without a dynamic model we can illustrate the mutual dependence of the five factors. We sketch a few in what follows.

4 Inclusive Wealth and Collective Well-Being

It is now becoming a commonplace that *inclusive wealth* is the right measure of economic well-being. An economy's inclusive wealth reflects the social value of its stocks of produced capital (roads, ports, buildings, machines), human capital (health, education) and natural capital (ecosystems, minerals, and fossil fuels). As accounting prices reflect social values, an economy's inclusive wealth can be read as the accounting value of the stocks of all its assets. The idea is not to dismiss GDP from national accounts (GDP is useful for short run

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[5] Heidi Albers' illuminating paper in this symposium (Albers, 2022) describes institutional arrangements best suited to undertake such investment.

macroeconomics management), but to create a parallel system of capital accounts, akin to firms' balance sheets, for judging economic performance.

There are forms of natural capital, such as the atmosphere and the open oceans, that are not owned by anyone; but if agents in an economy have free access to them, they should be included in inclusive wealth. Free access to an asset (and ownership is included in this characterization) is the criterion for its inclusion. The accounting price of a global public good such as the atmosphere as a sink for our carbon emissions (e.g., *minus* 200 dollars per ton of carbon emitted) is the *sum* of the accounting prices of the asset enjoyed by each nation. This is the standard rule for the accounting price of public goods. Arrow et al. (2012, 2013) constructed a practical way to attribute the global social cost of carbon among countries.

Accounting prices have ethical values embedded in them. The Endangered Species Acts in the US and UK point to that: they place an unbounded value on endangered species. Environmental economists have long recognised the intrinsic value of Nature. Freeman (2003), for example, reports extensively on the subject when describing contingent valuation exercises on environmental amenities and endangered species. To develop the economics of biodiversity, however, I encouraged readers to confine themselves to the use-value of ecosystems. I did that because I wanted to show that even that minimalist picture tells us we have been doing untold harm to ourselves by degrading Nature without having to enter controversies over what Nature's intrinsic value is. And I showed that using quantitative estimates. However, the idea of intrinsic value of living organisms, species, and ecosystems appears in various places in the *Review*. Moreover, Chap.12 ("Valuing Biodiversity") contains two sections (Sect.12.6 - "Nature's Existence Value and Intrinsic Worth: Sacredness" - and Sect.12.7 – "Nature's Intrinsic Worth: Moral Standing" - pp. 309–313) that not only speak about Nature's intrinsic value but also report that people all round the world are known to try to protect ecosystems that are sacred to them. I emphasised that sacredness is not tied to religious belief. The chapter moreover offers considerations that point to Nature's *moral* standing, a far deeper matter.

In his contribution to the symposium Nicolas Treich thinks that the number of pages devoted to a subject (his 32 pages as against my 5 pages in a 10-page chapter) is a measure of an author's engagement with it (Treich, 2022). The *Review* too would have had dozens of pages on the intrinsic value of Nature if I had felt readers would want to know which scholar wrote what on the subject while not bothering to ask after empirical estimates. It is easy enough to quote philosopher scholars on the intrinsic value of Nature, it is a lot harder to unearth how and why societies have allowed their sense of even the sacred to be trumped consistently by economics and the pursuit of gratification. The *Review* can be read as an attempt to understand that complex of issues.

Inclusive wealth is not an ad hoc measure, plucked from air. It has firm normative foundations: It can be shown that *inclusive wealth increases over time if and only if well-being across the generations increases over time* (*Review*: Ch. 13); moreover, *the (net) present value (PV) of a policy (e.g., an investment project) is the contribution it makes to inclusive wealth* (*Review*: Ch. 13). The pair of equivalence theorems tells us that inclusive wealth and well-being across the generations are two sides of the same coin. Inclusive wealth is therefore the measure with which to conduct both *sustainability assessment* and *policy analysis*.[6]

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[6] A project's PV, being the weighted sum of the flow of net benefits it generates, has the dimensions of a stock. The two equivalence theorems were proved in Dasgupta and Mäler (2000), and Arrow, Dasgupta, and Mäler (2003a, b). Arrow et al. (2004) offered a perspective on the idea of sustainable development and con-
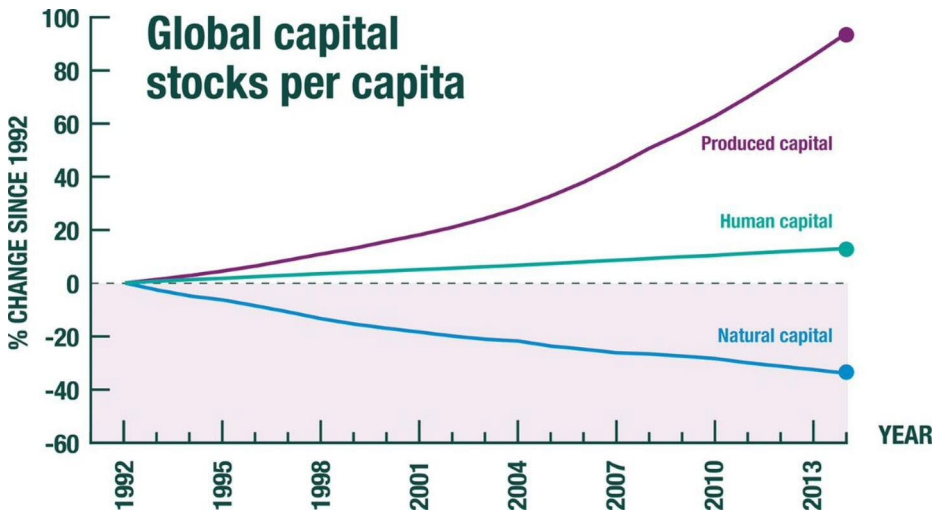
Fig. 1 Global Capital Stocks per Capita 1992–2014. Source: Managi and Kumar (2018)

UNEP has pioneered the construction of time series of inclusive wealth for over 120 countries (IHDP-UNU/UNEP, 2012, 2014; Managi and Kumar, 2018; Kumar, 2019). A striking finding in Managi and Kumar (2018) is that over the period 1992–2014, per capita global produced capital doubled in size, per capita global human capital increased by some 15%, but per capita global natural capital declined by 40% (see Fig. 1). The authors also found that inclusive wealth per capita has declined in recent years in more than 40 countries, many in sub-Saharan Africa. The performance of countries has almost certainly been worse than what the publications report because many maintenance and regulating services were unaccounted for.

It is a simple matter to deduce from the equivalence theorem for sustainability assessment that *a nation's inclusive wealth would increase over a period if aggregate consumption in the period was to be less than net domestic product* (that is, GDP less depreciation of capital assets). So, we have a criterion for sustainability based on flow accounts. My understanding is that national statistical offices in an increasing number of countries are creating natural capital accounts, not as a substitute for national income accounts, but complementary to them.

We should not expect national statistical offices to construct full blown inclusive wealth accounts. For one thing, accounting prices of natural capital are often deeply contentious; for another, the stocks are frequently hard to measure. The best that can be expected are natural capital accounts that offer qualitative descriptions of their state, for example, whether the health of an ecosystem has improved over the previous year or whether it has deteriorated. Even that would be valuable information. Of all the features of the *Review*, its advocacy of inclusive wealth as a measure of economic success has attracted the greatest attention among readers.

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trasted it with the idea of optimal development. Arrow et al. (2012, 2013) applied the theorem to study economic development in Brazil, China, India, USA, and Venezuela over the period 1995–2004. The countries were chosen deliberately, to highlight specific features that colour the prospects for economic development.

5 Global Payments for Ecosystem Services

Imagine a chain of supermarkets so inefficient at their check-out counters that customers take home most of what they pick without paying for them. Pilfering enables people to enjoy a high living standard, but it is bound to prove short lived, as the chain is guaranteed to go bankrupt. We don't pay for vast quantities of maintenance and regulating services, which means the high standard of living rich countries currently enjoy comes at the expense of future living standards. Here are three examples of why our use of the biosphere amounts to pilfering from Nature: [7]

1 Environmental Subsidies The aggregate subsidy humanity pays itself to "mine" Nature (e.g., energy subsidies) is of the order of 4–6 trillion US dollars annually, or some 5–7% of global GDP. That amounts to a negative price for Nature and creates an enormous pressure on the world's ecosystems. The subsidies provide us with a string of incentives to plunder the biosphere, not preserve it.

2 Global Commons We don't pay for such global public goods as the open seas and tropical rainforests. The former is an open-access resource (they lie beyond exclusive economic zones), suffering from the "tragedy of the commons". The latter are located within national jurisdictions, meaning that national incentives to conserve them are less than the global incentive.

3 Trade and Wealth Transfers It is not an accident that the bulk of the world's biodiversity is in the tropics and that most of the world's poorest people live there. Principal exports from those regions are primary products, whose extraction (from mines, plantations, wetlands, coastal waters, forests) inflicts adverse externalities on *local* inhabitants. The externalities are not reflected in export prices, meaning that local ecosystems are overexploited. But that amounts to a transfer of wealth from the exporting country to the importing country, that is, from a poor country to a rich country. If the emphasis in recent decades on trade liberalization is anything to go by, such wealth transfers as above are probably not appreciated. Propositions on the benefits of free trade suppose that all goods and services have perfectly competitive markets. The economics of biodiversity is perforce built for a world where markets are missing for many of Nature's services. The *Review* departs from economic orthodoxy most strongly on this point. [8]

Policy implications arising from the three examples drawn from the contemporary economic world suggest themselves. The moral to be drawn from example 1 (environmental subsidies) is obvious. But perhaps it is *because* the directive is obvious that there have been few attempts at assessing quantitatively the effect on our consumption patterns if the subsidies were removed. On the one hand, an immediate effect would be an increase in commodity prices and therefore lower disposal incomes; on the other hand, reduced taxation would mean an increase in our disposable incomes. Moreover, production structures would change over time, and there would be distributional effects. The key point though is that removing the subsidies would lead to consumption moving away from Nature intensive goods. Reduction in the Impact Inequality would trace it to a combination of changes in y, α, and S.

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[7] In his contribution to this symposium Ed Barbier offers an excellent study of the distortions we have created in our use of Nature's services (Barbier, 2022).

[8] In her illuminating contribution to this symposium, Amy Ando (2022) speaks of the inequities that persist because institutions stifle the voice of the less powerful, even in the design of valuation methods. The *Review* (Ch. 7–8) elaborates with the help of several examples how that can happen even inadvertently.

The oceans have received far less attention among national and international decision makers than the atmosphere as a sink for our carbon emissions. But the seas are vital for our existence. Example 2 points to the need for an institutional mechanism that provides incentives to reduce pressure on them, that is, to reduce the stress inflicted on the oceans by commodity transportation, cruises, fishing, and pollutants emanating from land. The standard tools of public economics are regulations (e.g., quantity restrictions) and taxes. The former is enshrined in such policies as protected zones. They have weaknesses because the oceans are mobile. On the other hand, such policies can be reached by international agreements without the need for an international agency to implement them. That is their attraction. One problem with such schemes is that, even though the open seas are, to use a phrase popular in the 1970s, a "common heritage of mankind", the rents from their use would be enjoyed by users, not by the public.

The latter tool, taxation, has the merit that the rents would in principle accrue to us all. Which is one reason the *Review* advocated it. But to implement it requires an international agency. The *Review* suggested the establishment of an agency with the remit to monitor and charge for the use of the high seas (e.g., taxing ocean transportation, deep-sea fishing, and the refuse that is deposited into them by nations). That could raise billions of dollars annually, for a trillion or more dollars of merchandise are shipped annually across the oceans.

The other reason the *Review* advocated the taxation scheme is that the rents so collected could be used in part to pay nations to conserve the tropical rainforests in their jurisdiction. Currently, the rest of the world complains about the continual destruction of what remains of the world's rainforests, but little is done about it. Payment for ecosystem services is becoming familiar within nations; what the *Review* proposed was to extend such a payment system to the international sphere. [9]

The proposal has not found enthusiasm among national and international civil servants, on grounds that the world does not have an appetite for that grand an undertaking. Neither COP26 nor COP15, nor for that matter Stockholm 50+raised the matter. At the same time, I would judge from the response global decision makers have made to the *Review* that they agree the world needs to undergo transformative changes if the Impact Inequality is to be eliminated. At the end of World War II nations created the World Bank, the IMF, and the United Nations and its subsidiaries. The Marshall Plan was designed to lift Europe from ashes, and it helped to do that. Those were transformative steps. Ashes and rubbles are visible. The silent and invisible processes that are a characteristic of Nature escape our attention.

Example 3 (trade and wealth transfers) tells us that the global South should *collectively* impose export taxes on primary products. [10] That would ease pressure on their local ecosystems (e.g., rainforests and fisheries) and would also be a source of income for the exporting nations. The World Trade Promotion Organizations held their 2022 conference in Accra in May. The conference's brief was to find ways to raise GDP in African countries while encouraging companies to move toward sustainable policies. But the event fielded no quantitative models with which to ask whether GDP can be raised even while protecting the

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[9] A government minister in Gabon was recently quoted as having made a demand for such a payment. I do not know whether the *Review* influenced his thinking.

[10] Individually, exporting nations would not do this for fear of losing markets. The global South faces the familiar prisoners' dilemma over the export of primary products.

region's ecosystems, nor whether companies would adopt ecologically sustainable polices without export taxes.

If climate negotiations are taken as illustrative, it would prove hard for African nations to reach collective agreements. Scott Barrett has pioneered the design of institutions that are needed if international agreements for reducing collective distortions are to be reached and abided by. The *Review* is less than satisfactory on this vital subject. His paper in this symposium (Barrett, 2022) is a far-reaching contribution to it.

Although exports of primary products involve wealth transfers from exporting to importing countries, it is not an unalloyed benefit for importing countries. That's because the transfers carry with them risks for importing companies. Repeatedly, directors of investment companies and financial institutions have raised their concerns with me over the financial risks that investors experience because of our ecological overshoot. The *Review* (Ch. 5) contains formal models which trace the risks importing firms face to the risks of ecological collapse in the countries from which they import primary products. Insuring against such risks in the marketplace is not a viable option. In addition to the moral hazard that is inevitably present along long supply chains, the risks are positively correlated (e.g., if a wetland is damaged, pollination suffers in neighboring farms). What is needed are incentives for importing firms to *protect* ecosystems that are upstream in their supply chains, not to insure against their collapse. Investment in Nature would be the needed form of insurance.

One of the members of the Advisory Panel of the *Review*, the late Sir Roger Gifford, was convinced that maintaining the integrity of ecosystems in their supply chains is sound business practice for companies. Investment in the sources of primary products makes business sense, he told me, if for no other reason than that firms would enhance their reputation among investors. [11] He appreciated of course that a company that makes a unilateral move toward ecological stewardship faces risks should consumers not be ecologically minded: first movers don't necessarily have an advantage. There have however been examples where companies have enjoyed early move advantages by declaring their trade practices to be fair. It is hard to generalize from these experiences. How strongly investors and consumers feel about ethical practices matters.

One way out of their dilemma would be for companies to disclose conditions in their supply chains collectively. [12] Disclosure would be a substitute for missing markets. A way to do that would be to lobby the government to make disclosure mandatory. Once again, problems besetting collective action rears its head. Barrett's paper in this symposium points to the issues companies need to attend to if they wish to reduce financial risks from deteriorating ecosystems in the tropics. In the appendix to this paper an example is constructed for demonstrating how decision makers could estimate the accounting price of an asset that is expected to suffer collapse at an unknown date in the future. That is the first step in translating ecological risks into business risks.

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[11] Sir Roger greatly influenced my thinking on financial risks associated with ecological damage. Tragically, he died a few months after the *Review* was launched.

[12] That would be akin to disclosure over the content of food products. Consumers worry about their health, which is why governments in the West now require food manufacturers to disclose the content of their products. Disclosure here serves to reduce an adverse selection problem.

6 Human Numbers: Family Planning, and Reproductive Health

The Impact Inequality tells us that economic possibilities extending into the future should be viewed from the *population-consumption-environment* (PCE) nexus. And the nexus says that demography is an integral part of ecological economics and the economics of sustainable development.[13] Ironically, neither the authors of the UN's Sustainable Development Goals, nor COP26, nor COP15, nor even the celebrations that were Stockholm50+earlier this year considered what increases in human numbers to 10billion or more might imply for the biosphere. So, it is interesting to study why and to ask what we lose from that neglect.

An explanation commonly offered is that the source of humanity's overreach is not the size of global population but consumption in the global North. That the latter is a major factor is plain (the three examples of pricing distortions in Sect. 4 point directly to it), but an exclusive focus on it misleads. To see why, imagine that the standard of living in the OECD countries (a club of rich nations) were to be halved from the current 40,000 dollars PPP. It is easy to check that, other things equal, the ratio of our demand for the biosphere's maintenance and regulating services to its ability to meet that demand on a sustainable basis would drop from 1.7 to round 1.3. High consumption in rich countries is, to be sure, an important part of the reason for our ecological overshoot. But human numbers are also a reason.
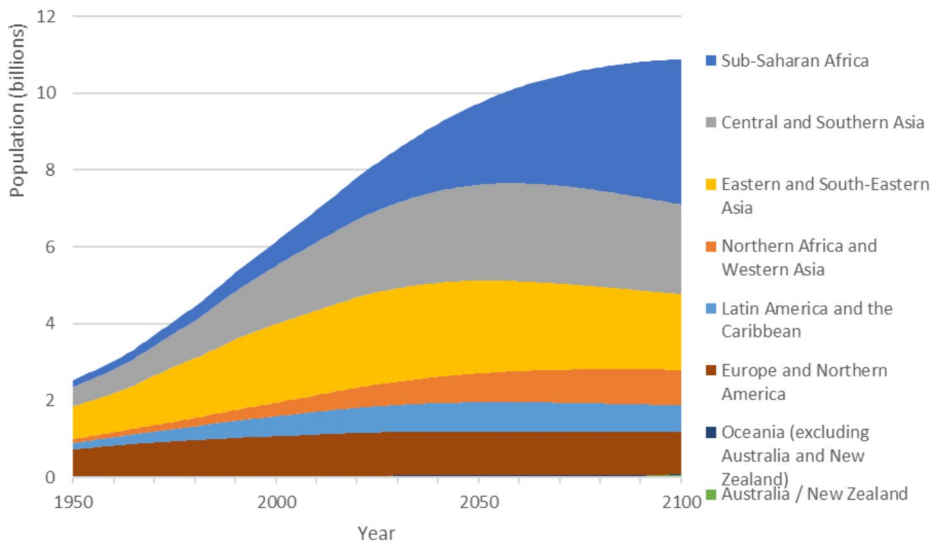
6.1 Global Population Projections

World population in 1950 was 2.5billion. Today it is 8billion. Figure 2, which presents the United Nations Population Division's population projections until 2100 (UNPD, 2019), sees global population in 2100 to be 10.2billion. These are UNPD's median estimates. The organization applies Bayesian updating methods to prepare their demographic projections. The lower bound of the 95% confidence interval for their projection is a global population of 9.8billion in 2100. Is that population size likely to be supportable at a comfortable standard of living on a sustainable basis? In a pen-and-paper exercise, Dasgupta, Dasgupta, and Barrett (2022) calibrated a widely used global production model by deploying current global figures for GDP, population size and the share of working-age people. The authors found that if 20,000 dollars PPP per year is taken to be a reasonable standard of living (it is average income in today's middle-income countries), the sustainable population is approximately 3.2billion, which was global population in the early 1960s. The finding can be read as an expression of how large the Impact Inequality is currently. Figure 2 shows that a great rise in global population took place in Asia from 1950. Rapid declines in mortality rates were not matched by reductions in fertility rates. Population in Asia grew from approximately 1.7billion in 1950 to 4.6billion in 2020. In the 1970s several countries in the Far East experienced a transition from high fertility rates (4 and over) to the replacement rate (2.1), but large young populations relative to the rest carried with them a momentum to keep population growing. [14]

Figure 2 also projects that population in all regions other than sub-Saharan Africa will level off or dip slightly from about 2050. In contrast, the median population projection for

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[13] For an elaboration, see Dasgupta and Ehrlich (2013) and Dasgupta and Dasgupta (2017).

[14] The fertility rate, usually referred to as the total fertility rate (TFR), is the number of live births a woman would expect to deliver over her reproductive years. The replacement (fertility) rate is the TFR that, in the long run, would stabilise population. It is taken to be approximately to be 2.1.

Fig. 2 Regional Population Projections 1950–2100. Source: UNPD (2019)

sub-Saharan Africa is a continual increase from today's approximately 1.2billion to 4billion in 2100 - a nearly four-fold increase from what it is today.[15]

Per capita GDP in sub-Saharan Africa is only about 25% of the global GDP per capita. The region's GDP is 3–4% of global GDP. That means sub-Saharan Africa is not responsible for today's *global* ecological overshoot. But the region's demands on its *own* ecosystems exceeds their ability to meet the demands on a sustainable basis; evidence for which is its deteriorating ecosystems (Managi and Kumar, 2018). The sub-continent suffers from a regional Impact Inequality (Wakernagel and Beyers, 2019). Which is why high fertility rates in the region can be expected to dampen the prospects of future Africans enjoying flourishing lives.[16] The region's ecological footprint will continue to rise as its numbers increase and attempts are made there to raise incomes by expanding its exports of primary products (example 3 in Sect. 4). To not acknowledge that is to commend policies that work against the interest of the common African citizen.[17]

6.2 Reproductive Culture and Demographic Transitions

Demography today has a deeply uneasy relationship with environmental activists, national governments, and international development organizations. I have found it hard to understand. One reason could be that *reproductive culture* is seen to be a slower changing factor in human behavior than other aspects of culture, such as for example, the rapid transition to eating fast food, wearing jeans, and participating in chat boxes that people in poor coun-

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[15] UNPD has updated its population projections recently, slightly larger than the figures I am quoting here.

[16] John Bongaarts has written extensively on the demographic problems facing Africa. See, for example, Bongaarts (2011, 2016, 2020).

[17] For a model that studies how a society can fall into a poverty trap in the population-consumption-environment nexus, see Dasgupta (2000). Bradshaw and Di Minin (2019) report that population density has been a driver of environmental degradation and biodiversity loss in sub-Saharan Africa.

tries have displayed in recent decades. However, reproductive culture is not as resistant to change as it is frequently imagined, for it has been known to adapt when people have found it in their interest to adapt *and* have the facilities to adapt. The rapid fertility transition in Taiwan from a high of 4 in 1970 to the replacement rate of 2.1 in 1984 – a mere 14 years - is an example of how cultural norms can change rapidly in a society previously regarded as traditional.

It was an achievement of economic demographers to have shown empirically that households' reproductive behavior is as amenable to economic analysis as is their food consumption. That fertility rates decline as incomes grow, other things equal, is a finding in economic demography. The explanation usually offered is that income growth is traceable to rising wages, and rising wages – especially women's wages - in their turn raise the value of time, making childbearing and childrearing more costly (Becker, 1981). That piece of reasoning, however, was meant for market economies. It would not seem to fit rural societies in the world's poorest countries, where women are engaged in manual work no matter whether they are bearing children or rearing them.

In recent years women's education has instead been seen by international development experts and environmental NGOs as being the surest route to women's empowerment, including, for example, women's ability to control birth spacing and choose their family size. All governments today acknowledge the importance of investment in women's education, however, that it is a ready road to women's empowerment in poor countries is not borne by evidence, for education involves more than school buildings. Teaching material needs to be provided and teachers themselves should be qualified. There has also to be a guarantee that teachers take their classes, that children attend them and are in a fit state of health (e.g., free of intestinal worms) to be able to concentrate and learn. Achieving each requires citizens' insistence that each of the factors is attended to. There is evidence that the combination has proved hard to achieve in the world's poorest countries. Even today nearly 30% of women between 15 and 24 years of age in low-income countries are illiterate. Moreover, what qualifies as literacy is woefully inadequate for the modern world.

The SDGs were fashioned seemingly with little attention to either demography or the possible difficulties poor countries face in using investment in education as a springboard for women's empowerment. UNESCO (2021) estimates that to meet the goal in the SDGs of universal primary schooling by 2030, the number of teachers in sub-Saharan Africa will have to increase by 4.6 million; and to achieve universal secondary schooling by 2030 in the region will require an expansion of the number of teachers from 2.9 million to 10.8 million. Currently nearly 20% of sixth graders are illiterate and 30% are innumerate in a sample of 14 countries in sub-Saharan Africa[18].

Only about 50% of women in sub-Saharan Africa who want to avoid pregnancy currently use modern methods, which means some 200 million women there have an unmet need for family planning and reproductive health services (Bongaarts, 2016). The fertility rate in sub-Saharan Africa is 4.6, and population is projected to grow at 2.6% a year over the coming future. Nigeria's TFR is 5.4 and the country is expected to grow from a population of 200 million today to some 380 million in 2050. That's UNPD's median projection. Within the 95% uncertainty range, Nigeria's population in 2050 is projected to lie between 300 million and 480 million, depending on the socio-economic scenario that is sketched. Much can be gained by bringing forward a fertility transition. A transition in Nigeria, more

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[18] I am grateful to Aisha Dasgupta for discussions on the quantitative estimates I am collating here.

generally in sub-Saharan Africa, to a replacement rate in, say, 20 years' time rather than in 50+years' time would mean a massive lowering of the projected population size in 2070, which in turn would reduce the pressure population in the sub-continent would inflict on their local ecosystems.

In several events I participated in since the *Review* was launched, I heard it suggested instead that sub-Saharan Africa's high fertility rates are a harbinger of a demographic dividend. That is a misleading reading drawn from East Asia's experience in the 1970s, where fertility rates dropped sharply to below replacement level in a brief number of years. The dividend was a reduced share of *non*-working age people, enabling saving rates to increase. Sub-Saharan Africa's situation is entirely different. Continual population growth sustains an age distribution where an increasing number of youths find themselves in need of employment in an environment where savings rates are low. In Nigeria, for example, the population in prime working age (20–64 years) is projected to increase from about 90 million to nearly 200 million between 2020 and 2050. The country therefore needs to create nearly 4 million additional jobs a year. The unemployment rate is currently about 33%, of which 50% are youths. The ratio of population in age group 20–64 to total population is expected to rise from a bit over 40% to nearly 60% in the period. Meanwhile, nearly 60% of the population experience modest to severe food insecurity and some 65% of the urban population live in slums.[19]

Indifference toward demography as a factor in sustainable development is reflected in the OECD's practice of allocating less than 1% of their aid budget to family planning and reproductive health. The UK government in its last budget reduced its meagre allocation to family planning by 85%. For international organizations and national governments to seek to empower women while neglecting to offer the services women need to exercise control over their own bodies by spacing pregnancies and choosing their family size, and for development and environmental NGOs to support that neglect, is unconscionable.

6.3 Reproductive Rights

Absence of demography in environmental and development thinking is only a recent phenomenon. The United Nations Population Division (UNPD) of the Department of Economic and Social Affairs conducts demographic research. Among other things, it assists countries to develop their capacity to produce and analyze national demographic data. Established in 1946 to serve the UN Population Commission, it is today the world's premier and most reliable source of information on global population. The Commission's publications show that a nation's demographic structure was once taken to be an essential factor in development possibilities. Which may be why the commission was renamed in 1994 as the Commission on Population and Development. However, earlier that same year the International Conference on Population and Development, held in New Delhi, reaffirmed the language of rights in the sphere of family planning and reproductive health. The Conference's conclusions stated:

"Reproductive rights … rest on the recognition of the basic right of all couples and individuals to decide freely and responsibly the number, spacing, and timing of their children, and to have information and means to do so, and the right to attain the highest standards of sexual and reproductive health" (UNFPA 1995: Ch. 7, Sect.3).

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[19] In addition, corruption is rife in that oil rich country and is acknowledged to be so by Nigerians themselves.

The fundamental right of individuals to decide freely and for themselves whether, when, and how many children to have, is central to the vision and goals of the UN's Family Planning 2020 and is also pivotal in the reproductive health indicators of the Sustainable Development Goals. But even while it has become a commonplace to point to reproductive rights, it is not often asked whether the conditions underlying reproductive choices envisaged in the Conference's statement are being met.

The conditions would not be met if the institutions within which reproductive decisions are made are an inappropriate setting for an unbridled use of the language of rights. Three circumstances are worth noting (Dasgupta and Dasgupta, 2017, 2022). They vary in their importance depending on the situation:

(a) Social embeddedness of household reproductive preferences: specifically, the average family size of their peer group (e.g., neighbors) influences a household's preferred family size.
(b) Lack of access to modern family planning and reproductive health services.
(c) Increase in the global ecological footprint from additional births.

That the Impact Inequality points to a clash of rights between us and our descendants ((c)) is of course the basis of the *Review*. We have also noted that millions of women in sub-Saharan Africa suffer from (b). So, I shall focus on (a) and consider situations where household preferences are *conformist*, that is, where no household wants to choose in a way that differs greatly from their neighbors' choices.

That our reproductive preferences are conformist is a reason fertility transitions have been known to take place rapidly. They are also a reason a society's fertility rate can remain high for a long spell. The two features are an expression of the fact that conformist preferences can give rise to multiple social equilibria, akin to the multiple equilibria in coordination games. As a stylized example, consider a society where, if all other households have 5 children the typical household's goal is to have 5 children, but if all other households have 2 children the typical household's goal is to have 2 children. It could be that both are stable situations, and it can be that even though households would prefer to reside in the latter state of affair, they are trapped in the former. If that were so, households would find it in their *own* interest to discover ways to create a structure of incentives that leads them to alter their reproductive practice. A move from the high fertility equilibrium to the low fertility equilibrium would amount to a fertility transition. Family planning and reproductive health programs that engage communities have been found to be effective in bringing about such a transition. No coercion is required.[20]

Economic demographers until recently have assumed instead that households are *solipsistic*. Pritchett (1994), for example, regressed actual fertility rates (TFRs) on wanted fertility (WTFR) in 43 countries in Asia, Africa, and Latin America and found that about 90% of cross-country differences in TFR are associated with differences in WTFR. He also found that excess fertility (TFR – WTFR) was not systematically related to actual TFR, nor an

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[20] I have heard it suggested by development activists that even when coercion is not overt in family planning programs, it is present in subtle forms. It is hard to know what to make of the claim, other than to point out that by the same token programs that are designed to drop unhealthy food habits, more generally unhealthy lifestyles, presumably also have subtle forms of coercion built into them. And if we are so minded, even "nudge," a practice that is increasingly being adopted by governments to make it easier for us to choose in ways that serve our own best interest, can be read as involving subtle forms of coercion.

important determinant of it. The author concluded that high fertility is due entirely to the strong desire for children.

The study has been found to be wanting (Lam, 2011). Nevertheless, imagine the finding had been robust. Pritchett's conclusion may follow if households are solipsistic, but not if they are conformists. If fertility preferences were conformist, it would tell us we should expect a correlation between TFR and WTFR, but it also would also warn us not to attribute causality to the relationship. For it would then be as true to say fertility rates in those countries where they are high are high because people have a strong desire for children as it would be to say that people there have a strong desire to have children because fertility rates are high (Dasgupta and Dasgupta, 2017).

Evidence that reproductive preferences, like consumption preferences, are conformist has been found in historical studies (Watkins, 1990) and analyses of natural experiments (e.g., Jensen and Oster, 2009). And there are many more studies in hand that confirm that we are not individually solipsistic.

6.4 Community Based Health and Family Planning Programs

Keeping demographic choices out of discussions on sustainable development reflect political sensitivities, presumably born out of a revulsion toward the programs introduced in China and for a brief while in the late 1970s in India. But demographic transitions have been experienced many times over in environments where coercion was not part of government practice (Bongaarts and Sinding, 2011). In recent decades they have involved instead community-based health and family planning programs. A substantial literature has offered a quantitative feel for the returns from investment in family planning and reproductive health when measured in terms of reductions in maternal, infant, and child mortality rates, among other measures of health and well-being.[21]

The success of Bangladesh in bringing about a fertility transition even while the literacy rate among women remains a low 70% speaks to the significance of such social programs. The programs designed there - and NGOs had an enormous presence in them, as in the famous Matlab Thana experiment (Joshi and Schultz, 2013; Bongaarts, 2016) - have involved providers working with households and village leaders in bringing the facilities to the doorstep. Male partners were involved in discussions. Utterly poor in 1971, when the country was founded, Bangladesh is today a middle-income country in the World Bank's rankings, with a per capita GDP of 2,500 USD.

Comparison with Pakistan is revealing.

Table 1 Fertility behavior in the two countries have diverged:

	Fertility Rate in 1971	Fertility Rate in 2019
Bangladesh	6.94	2.0
Pakistan	6.60	3.4

Moreover, GDP per capita in 1971 in West Pakistan (now Pakistan) was about 40% greater than what it was in East Pakistan (now Bangladesh). Today it is about 40% smaller

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[21] Phillips, J.F. et al. (2003), Canning and Schultz (2012), Joshi and Schultz (2013), Kohler and Behrman (2014), Guttmacher Institute (2017), Jensen and Crenin (2020), Kavaki and Rotondi (2022), and Kavra et al. (2022) are among recent publications.

(GDP per capita, 1,540 USD). The population size of Bangladesh is today approximately 165 million, that of Pakistan 225 million. Under the projection made by UNPD (2017), the population size in the two countries will be 175 million and 350 million respectively. The projected increase in difference in the size of population in the two countries – from 60 million to 175 million – is due to the cumulative effects of seemingly small differences in their fertility rates.

7 Political Sensitivities and the New Consensus

Bangladesh's is of course only one example of success. East Asian countries made the fertility transition decades earlier. Nevertheless, I have encountered only silence at any mention that sub-Saharan Africa's demographic trajectory may pose enormous problems for future people in that region. The *Review* speaks to global and regional population numbers and the salience of family planning services in addressing the problems of climate change and biodiversity loss (Ch. 9), but it is the chapter most commentators have preferred to skip.

My sense is that there is a consensus among national and international decision makers over the language in which the idea of sustainable development is to be framed. In the many meetings I have had since the *Review* was launched, involving environmental and development NGOs and decision makers in national governments and international organizations – be they women or men, be they from the global North or the global South - I found them with rare exception to be speaking a common language. That language reflects a new consensus on economic development, built round the UN's Sustainable Development Goals. There would appear to be a tacit understanding among decision makers in donor countries and those in aid-receiving countries that investment in family planning and reproductive health is not part of that language. NGOs in the fields of environment and development comply, perhaps because they rely on funding from those very people.

Whenever I have asked privately why population is a taboo word in official international circles, I was told it is to respect cultural sensitivities. Whose, though? There is no evidence those sensitivities are reflected in the desires and aspirations of the more than 200 million women in sub-Saharan Africa who have an unmet need for family planning. So, I can only think that it is political, not cultural sensitivities that are in play. And those political sensitivities have been shaped by the sensibilities of decision makers who have a similar cultural background, no matter whether they are men or women, or whether they come from the global North or the global South. They have attended the same institutions (in the West) for advanced studies, know one another through conferences and meetings, and want to avoid discussing what may be embarrassing issues for some among them.

Do my impressions come across as overwrought? Perhaps they do, but consider this:

At the meeting in Accra in May 2022 of the World Trade Promotion Associations, I was invited to deliver the keynote lecture following the conference's opening by Ghana's President. The conference's facilitator, the International Trade Centre, based at the Palais de Nations in Geneva, pre-recorded my speech as I would be unable to attend in person. Quite by accident I discovered a few days before the event that the organisers at ITC had erased the last remarks in my lecture, where I had raised Africa's demographic problems. In the event we agreed I should be removed from the program and my lecture should be cancelled.

8 Appendix

Risk-Adjusted Accounting Prices.

How does the risk of ecosystem collapse at the top end of the supply chain of a company translate into the company's risks? We study that by deriving the adjustment that firms should make to the value they attribute to ecosystem services.[22]

Time is continuous, denoted by $t \geq 0$. Suppose a supply source (e.g., a wetland) of size S, yields benefit of P dollars per unit of the source to a firm. We begin by assuming P is constant. The discount rate the firm applies to future benefits from the supply source is r. We assume $r > 0$.

So long as supply source remains intact, the flow of benefits from it is PS at each moment. If the firm is certain that it would remain intact forever, the supply source would be worth PS/r to it. But because ecosystems are being degraded everywhere, the firm fears that the source will collapse at an uncertain date. The case where the uncertainty is characterized by a Poisson process, with a hazard rate h, is trivial, as it means that the value of the supply source to the firm is $PS/(r+h)$. So, we consider a different scenario. We suppose that the source will collapse at a random date in the next T years. We study the case where the uncertainty is uniform. Formally, at $t=0$, there is a constant probability rate $1/T$ of the supply source collapsing.

But that's the distribution at $t=0$. Bayesian updating tells us that conditional on the supply source surviving until t, the probability rate that it will collapse at any date in the interval $[t, T]$ is $1/(T-t)$. Viewed from $t=0$, the probability rate that the source will survive until t, is thus $(T-t)/T$. The *hazard rate* at t is $1/(T-t)$, which goes to infinity as t tends to T. We now apply this to calculate the risk-adjusted accounting value of the supply source.

As the probability that the supply source will exist until t is $(T-t)/T$, its expected worth to the firm is:

$$PS \left\{ {}_0\int^T \left[e^{-rt} \left(T - t \right) /T \right] \mathrm{d}t \right\} = [PS/r] \left[1 - e^{-rT} \right] - [PS/T] \left[{}_0\int^T \left\{ te^{-rt} \right\} \mathrm{d}t \right] \text{(A.1)}$$

Write the risk adjusted value of S as a function of T as $F(T)$. Integrating the final term on the right-hand side to eq.(A.1) by parts yields:

$$F(T) = [PS/r] \left[\left(1 - \left(1 - e^{-rT} \right) /rT \right] \right. \tag{A.2}$$

In short, the risk adjustment term $R(T)$ is.

$$R(T) = \left[1 - \left(1 - e^{-rT} \right) /rT \right] \tag{A.3}$$

It is simple to confirm that $\mathrm{d}F(T)/\mathrm{d}T > 0$. Thus, $F(T)$ is a monotone increasing function of T in the interval $[0, \infty)$. Moreover, $F(T) \to 0$ as $T \to 0$ and $F(T) \to PS/r$ as $T \to \infty$. Both

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[22] I am grateful to Matthew Agarwal, who asked me how the risk of ecological collapse modifies accounting prices.

limits are exactly as intuition would direct us to. Moreover, the risk-adjustment factor, R, lies between 0 and 1. That too is exactly what one would expect. The example, albeit stylized, has a general message. Risk of ecological collapse translates into a risk factor, between 0 and 1, on an ecosystem's value.

An extension of the model worth considering here involves abandoning the assumption that P is a constant. With the world's rainforests being razed to the ground to make way for cattle ranches, plantations, and mines, we would expect the benefits from S to increase over time relative to our assumed *numeraire*, income. The simplest assumption is that P increases exponentially at, say, the rate $\beta > 0$, that is, $P(t) = P(0)e^{\beta t}$. For clarity, assume that $r > \beta$. We may then replace r by $(r-\beta)$ in eq.(A.2)-(A.3). That is, the risk adjusted accounting price of the source is larger, the larger is β. Moreover, $P(0)SR/(r-\beta) \to P(0)ST/2$ as $\beta \to r$. That too is exactly what intuition would suggest.

A further extension involves coupled ecosystems. Consider a pair of symbiotic ecosystems S_1 and S_2 yielding benefit flows P_1 and P_2 per unit of the respective ecosystems. We could think of S_1 as a mangrove forest and S_2 as a coral reef. To avoid studying dynamics, we begin by imagining that adjustments in one to a perturbation in the other is instantaneous. Their symbiosis can then be represented by the function $S_2(S_1)$, with $dS_2(S_1)/dS_1 > 0$ and $S_2(0) = 0$. The risk adjusted accounting price of the coupled system is then.

$$F(T) = [(P_1 S_1 + P_2 S_2)/r] [(1 - (1 - e^{-rT})/rT] \tag{A.4}$$

A simple extension of the coupled system would be a lagged response. Suppose that if ecosystem "S_1" were to collapse at t, the coupled ecosystem "S_2" would remain intact until $t+L$, at which moment it too would collapse. Define $V(L)$ as.

$$V(L) = P_2 S_2 \left[{}_0 \int^L (e^{-rt}) \, dt \right] = P_2 S_2 (1 - e^{-rL})/r \tag{A.5}$$

It follows that.

$$F(T) = [(P_1 S_1 + P_2 S_2)/r] [(1 - (1 - e^{-rT})/rT] + V(L)[1 - (1 - e^{-rT})/rT] \tag{A.6}$$

Applying eq.(A.5) in eq.(A.6) yields.

$$F(T) = [(P_1 S_1 + P_2 S_2/r][1 - (1 - e^{-rT})/rT] + P_2 S_2(1 - e^{-rL})[(1 - e^{-rT})/rT] \tag{A.7}$$

The ecosystems would be independent of one another if $L = \infty$. In which case eq.(A.7) reduces to.

$$F(T) = P_1 S_1 [1 - (1 - e^{-rt})/rT] + P_2 S_2/r$$

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