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Weak versus Strong Sustainability

EXPLORING THE LIMITS OF TWO OPPOSING PARADIGMS

Eric Neumayer

FIFTH EDITION

Weak versus Strong Sustainability

To my students, the past, current and future ones

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Exploring the Limits of Two Opposing Paradigms, Fifth Edition

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w	Parameter
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λ	Shadow value of man-made capital General Lagrangian multiplier
μ	Shadow value of the stock of non-renewable resources
ω	Shadow cost of the stock of resource discoveries
ϕ	Shadow value of the stock of renewable resources
ψ	Shadow cost of the stock of pollution
ξ	Shadow value of the stock of human capital
ρ	Pure rate of time preference
η	Elasticity of the marginal utility of consumption Lagrangian

Abbreviations and acronyms

Abbreviations that are rather unfamiliar are explicated in the main text on their first appearance. Familiar abbreviations are used without further explanation throughout.

AES	Allen partial Elasticity of Substitution
AIDS	Acquired Immune Deficiency Syndrome
bn	billion (thousand million)
CBA	Cost-Benefit Analysis
CES	Constant Elasticity of Substitution
CFC	Chlorofluorocarbons
CO_2	Carbon Dioxide
CV	Contingent Valuation
DDT	Dichlorodiphenyltrichloroethane
DICE	Dynamic Integrated Model of Climate and the Economy
DNA	Deoxyribonucleic Acid
EF	Ecological Footprint(s)
EKC	Environmental Kuznets Curve
ENetS	Extended Net Saving
FAO	Food and Agricultural Organization
GDP	Gross Domestic Product
GEF	Global Environmental Facility
gNNP	green Net National Product
GNP	Gross National Product
GPI	Genuine Progress Indicator
GREENSTAMP	Greened National Statistical and Modelling Procedures
GS	Genuine Savings
HDI	Human Development Index
IPCC	Intergovernmental Panel on Climate Change
ISEW	Index of Sustainable Economic Welfare
LDC	Less Developed Country
MF	Material Flows
MRS	Marginal Rate of Substitution
NO_x	Nitrogen Oxides

NPP	Net Primary Productivity
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
R&D	Research and Development
RICE	Regional dynamic Integrated Model of Climate and the Economy
SD	Sustainable Development
SHDI	Sustainable Human Development Index
SI	Sustainable Income
SMS	Safe Minimum Standard
SNI	Sustainable National Income
SO_x	Sulphur Oxides
SS	Strong Sustainability
UK	United Kingdom
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
US	United States of America
WBCSD	World Business Council on Sustainable Development
WS	Weak Sustainability
WTA	Willingness-to-accept
WTP	Willingness-to-pay

Preface to the fifth edition

This fifth edition of *Weak versus Strong Sustainability* is the most substantive revision of all previous editions (Neumayer 1999a, 2003c, 2010, 2013). This is partly because the fourth edition is from more than a decade ago and so much has happened in the meantime. The revisions run throughout the book, but Chapters 4 to 6 have seen particularly large changes. Chapter 4 newly discusses safe operating spaces within planetary boundaries as another approach for coping with risk, uncertainty, and ignorance. The World Bank has changed its preferred measure of weak sustainability from net adjusted savings, also called genuine savings, to the change in total wealth per capita, and this has had a major impact on Chapter 5. Similarly, the strong environmental sustainability index has replaced sustainability gaps as one of the measures of strong sustainability in Chapter 6, and the discussion of physical strong sustainability measures has been expanded at the expense of hybrid (physical-cum-monetary) measures. I have also updated all graphs and tables, and I discuss the literature published since the last edition was published throughout the book.

I have tried to ensure that the book is open to a broad audience. I hope to have written a book that is accessible to all with an interest in the two opposing paradigms of weak and strong sustainability, whether they are economists or not.

This book builds upon articles in refereed journals and has therefore benefited greatly from many comments of anonymous referees as well as participants at research seminars and international conferences. It has benefited much from discussions with the participants of these events, as well as from comments from James Putzel (special thanks), Brian Barry, James K. Boyce, Lord Meghnad Desai, Simon Dietz, Paul Ekins, Salah El Serafy, Henk Folmer, Mathias Hafner, the late Kirk Hamilton, Friedrich Hinterberger, Michael Jacobs, the late David Pearce, Tom Tietenberg, Jeroen C.J.M. van den Bergh, and Mathis Wackernagel. All errors are mine as are all views expressed here.

Besides my current, past, and future students, this fifth revision is also dedicated to the late great Herman Daly. I am often very critical of his writings in this book, but he has been a great inspiration over many years, and he is a giant of ecological economics and strong sustainability. I am deeply grateful for all his contributions to the sustainability debate and his endorsement of this book.

Eric Neumayer

1. Introduction and overview

Starting from the early 1990s, support for 'sustainable development' (henceforth: SD) had become widespread. At the Rio summit in 1992, the vast majority of nation-states formally committed themselves to SD by signing Agenda 21 (UNCED 1992) – a commitment renewed at the 2002 World Summit on Sustainable Development in Johannesburg and the 2012 Earth Summit, also known as Rio+20. In 2015, the United Nations General Assembly adopted a bewilderingly wide-ranging set of 17 Sustainable Development Goals (SDGs), which set targets to be achieved by 2030 (https://sdgs.un.org/goals). While the rhetoric has shifted somewhat as fads come and go, it remains true that since the early 1990s there has been hardly any politician, academic, or businessperson who does not call for making development sustainable. In some sense this is not surprising: SD is like freedom or peace – that is, something to which no reasonable person would overtly object. Development always sounds good, and that it has to be sustainable seems self-evident.

In this book, two economic paradigms of SD – 'weak sustainability' and 'strong sustainability' – will be analysed with the objective of exploring their limits. 'Weak sustainability' (henceforth: WS) is based upon the pioneering work of two neoclassical economists: Robert Solow (1974a, 1974c, 1986, 1993a, 1993b), a Nobel Laureate, and John Hartwick (1977, 1978a, 1978b, 1990, 1993), a famous resource economist. WS can be interpreted as an extension to neoclassical welfare economics. It is based on the belief that what matters for future generations is only the total aggregate stock of 'man-made'[1], human and 'natural' capital[2] (and possibly other forms of capital as well, such as social capital), but not natural capital as such. Loosely speaking, according to WS, it does not matter whether the current generation uses up non-renewable resources, degrades renewable resources, destroys environmental amenities, or pollutes the environment as long as enough machineries, roads, and ports, as well as schools and universities, are built in compensation. Because natural capital is regarded as being essentially substitutable in the production of consumption goods and services and as a direct provider of utility, I call WS the 'substitutability paradigm'.

In opposition to WS stands 'strong sustainability' (henceforth: SS). While WS is a relatively clear paradigm in that it builds upon a well-established core of neoclassical welfare economics, SS is not. It is more difficult to define SS and pin down its implications, as many different scholars have contributed their own views on what SS should be. However, the essence of SS is that natural capital is regarded as non-substitutable, in the production of consumption goods and services ('source' side of the economy), in its capacity to absorb pollution ('sink' side of the economy), and as a direct provider of utility in the form of environmental amenities. The latter represents a sometimes-neglected aspect of natural capital despite strong evidence that the ability to access greenspaces and experience nature in its multifaceted ways, which represent important aspects of environmental amenities, contributes significantly to human health and well-being (Willis 2024). Hence, I call SS the 'non-substitutability paradigm'.

The objective of this book is to explore the limits of the two opposing paradigms of sustainability. In particular, it will assess whether either paradigm can provide a clear course of action and a measure or indicator[3] for whether sustainability is achieved or not. The book is thus an exercise in exploring the limits of what one can know about the requirements of sustainability.

The book is structured as follows. Chapter 2 discusses conceptual, ethical, and paradigmatic issues of SD. The definitions, assumptions, and the methodology of the analysis in the book are laid down. Then arguments are presented which make SD plausible as an ethical choice. A kind of time-inconsistency problem of SD is discussed, which results from the fact that the current generation can only commit itself, but not coming generations, to SD. Finally, two misunderstandings about what sustainability requires are corrected. It is shown that SD neither locks society into eternal poverty if it is poorly endowed at the start nor demands the choice of greatly inferior utility paths. These ethical issues of SD are dealt with before a distinction is made between WS and SS because they apply to both paradigms equally.

Next, in Chapter 2, the two opposing weak and strong paradigms of sustainability are characterised. It is shown that WS can be interpreted as an extension to neoclassical welfare economics with the additional requirement of non-declining utility over time. The implications of the substitutability assumptions are explained. As regards SS, two differing possible interpretations are given. One calls for preserving natural capital in value terms,[4] the other one calls for preserving the physical stocks of certain forms of so-called critical natural capital. The implications of the non-substitutability assumption are explained.

After the two paradigms have been presented, Chapter 2 stresses the importance of the substitutability assumption using climate change as a case study. It is shown that cost-benefit analysis, as exemplified by the approach taken by Nordhaus (1991a, 1994, 2008, 2017, 2018, 2019a), comes to the conclusion that only minor emission cutbacks are efficient and therefore optimal unless the discount rate used is very low. The predominant critique of Nordhaus has concentrated on the rate of discount to be used. I argue that the more important issue is Nordhaus's implicit assumption of substitutability of natural capital. If one accepts the substitutability assumption, then it is highly questionable whether one can make a very persuasive case for using a relatively low discount rate. I therefore argue that substitutability should be the main issue in dispute, not discounting.

Chapter 3 analyses the validity of the basic assumptions of both paradigms. As mentioned, WS regards natural capital as being essentially substitutable both in the production of consumption goods and services and as a more direct provider of utility. SS, in contrast, regards natural capital as being essentially non-substitutable. Chapter 3 first examines theoretical and empirical evidence on the availability of natural resources for the production of consumption goods and services. Four propositions of resource optimism are stated and critically assessed. These propositions imply that a natural resource can either be substituted with another resource or man-made capital, or that the feedback mechanisms triggered by rising resource prices and technical progress will work to overcome any apparent constraint. Second, it discusses whether future generations can be compensated for long-term environmental degradation. It argues that an answer to this question must be speculative to some extent as one cannot know the preferences of future generations. It also argues that there are good reasons against both extreme positions; that is, neither unlimited substitutability nor perfect non-substitutability of natural capital as a provider of utility seems reasonable. As will be explained in Section 2.3.1, p. 24, WS tends to be rather optimistic about the environmental consequences of economic growth, however. It therefore does not need to rely on the assumption that natural capital is substitutable as a direct provider of utility. In other words, it does not really need to rely on the assumption that increased consumption opportunities can compensate future generations for the loss of natural capital in the form of long-term environmental degradation, which would be difficult to maintain. Chapter 3 therefore analyses, third, the link between economic growth and environmental degradation. The theoretical case both in favour of environmental optimism, which suggests economic growth is good for the environment at least over the long run, and environmental pessimism, which contends the opposite, are put forward. However, since the likely environmental consequences of future economic growth cannot be solved theoretically, the existing empirical evidence on this question is examined as well.

In short, Chapter 3 concludes that neither paradigm of sustainability is falsifiable. As is so often the case for extra-paradigmatic disagreements, support for one paradigm or the other depends largely on basic beliefs (here about possibilities of substitution and technical progress) which are non-falsifiable and therefore cannot be conclusively decided. The book offers an alternative explanation to that of Norton (1995) who argues that the debate between proponents of WS and SS cannot be resolved because there is no agreement on the scope of the true subject matter nor a consensually accepted methodology. Chapter 3 argues that it would still be impossible to resolve the debate even if there was agreement on the subject matter and a consensually accepted methodology.

That, strictly speaking, both paradigms of sustainability are non-falsifiable does not imply of course that scientific research cannot help in informing policy-making for sustainability. Chapter 4 takes up the discussion where it ended in Chapter 3 and argues that a combination of the distinctive features of natural capital with the prevalence of risk, uncertainty, and ignorance makes a *persuasive* case for the preservation of certain forms of natural capital that provide basic life-support functions. It argues that, in principle, there are good reasons for the protection of global life-support resources such as biodiversity, the ozone layer, and the global climate, as well as the restriction of the accumulation of pollutants. Conversely, no explicit protection policy for non-renewable resources used in the production of consumption goods seems warranted. In essence, therefore, Chapters 3 and 4 argue that there is more support for WS with regard to the 'source' side of the economy, while there is more support for SS with regard to the 'sink' side of the economy and with regard to natural capital as a direct provider of utility in the form of environmental amenities.

Chapter 4 discusses various ways of coping with risk, uncertainty, and ignorance in the form of the precautionary principle, safe minimum standards (SMSs), and safe operating spaces within planetary boundaries. One important question is how much cost society should be willing to incur to preserve certain forms of natural capital if policymakers pursue one of the approaches for dealing with risk, uncertainty, and ignorance. One option is to deliberately ignore opportunity costs. Given uncertainty and ignorance about the consequences of depleting natural capital, one might choose to refrain from any marginal decisions and call for the preservation of the remaining totality of certain forms of natural capital. From this perspective, it is better to incur the definite and potentially large costs of preservation to prevent the uncertain, but potentially tremendous, costs of depletion. However, I argue in Chapter 4 that it is better to face the fact that every policy decision for preserving natural capital implies an opportunity cost that has to be balanced against the benefits of preservation.[5] Deliberately ignoring opportunity costs is tantamount to avoiding the challenging decisions on how to spend scarce resources for which there are several competing claims. Chapter 4 therefore argues in favour of preserving critical forms of natural capital subject to the condition that preservation costs must not be 'unacceptably high', with preservation costs defined in net terms as opportunity costs minus the expected benefits of preservation.

I conclude Chapter 4 by suggesting that such a position is, in effect, broadly compatible with a moderate deontological or rights-based approach, which obliges the current generation to prevent imposing deliberate harm on the future unless the costs of following this prescription become excessive. Scientific research can help society by providing information on the likely benefits and costs of preservation. But it cannot tell society what it should regard as 'unacceptably high' costs. That is, it cannot tell society how risk-averse it should be with regard to the depletion of natural capital. The precautionary principle, SMSs, and safe operating spaces within planetary boundaries imply that opportunity costs may exceed the expected preservation benefits by a certain factor. Economic valuation techniques provide the best available information on both benefits and costs. But what constitutes 'unacceptably high' costs is an ethical and political question, not a scientific one.

Chapter 5 assesses whether WS, as defined in this book, can be measured in practice. The change in the total wealth per capita or in the stock of total capital per capita, which is the aggregate linear sum of individual forms of capital, is introduced. This is the theoretically correct measure now preferred by the World Bank, which is also the principal provider of empirical estimates, though the United Nations Environment Programme (UNEP) provides competing estimates as part of its Inclusive Wealth reporting. Prior to that, and therefore also featuring in previous editions of this book, the World Bank had preferred net adjusted savings, also called genuine savings, as the correct measure. Since net adjusted savings is investment in total capital stocks minus depreciation of total capital stocks, both measures are theoretically correct and should provide the same indication on the WS of countries and other units, even though, in practice, they are not quite the same due to differences in operationalisation.

The analysis then turns to the Index of Sustainable Economic Welfare (ISEW) or Genuine Progress Indicator (GPI), an alternative indicator of WS. Early studies purported to demonstrate the existence of a 'threshold effect' in the form of an increasing divergence between gross domestic product (GDP) per capita growing over time, on the one hand, and stagnating or even decreasing ISEW/GPI per capita, on the other. Early studies were typically based on methodological errors such as accumulating long-term environmental damage from year to year and problematic and highly implausible assumptions such as a 3 per cent escalation factor for the depreciation of the natural resource stock, which artificially and invariably create a 'threshold effect'. More recent studies avoid these errors and problems and come to more mixed findings. All ISEW/GPI studies suffer from the, in my view, insurmountable challenge of aspiring to measure both current welfare and sustainability in one single indicator. Contrary to the World Bank's and UNEP's measures of WS, the ISEW/GPI of different countries are not comparable with each other because there is no common agreed-upon methodology, and each individual study is somewhat idiosyncratic in what components it includes and how it measures them.

Next, Chapter 6 turns to measuring SS. The analysis in Chapter 4 implies that the second interpretation of SS should be favoured over the first one: it is more sensible to preserve the physical stocks of certain forms of natural capital (at least up to a certain extent). In contrast, preserving natural capital in value terms does not preclude the possibility that certain forms of natural capital providing basic life-support functions are endangered or become irreversibly lost. It is therefore not surprising that all indicators of SS I look at here are either physical indicators or hybrid indicators, which combine the setting of environmental standards in physical terms with monetary valuation.

In the first section on physical indicators, I present the justification and basic idea of the concept of ecological footprints (EF) and the concept of material flows (MF) as the two most important and popular physical indicators of SS. With respect to EF, I show that strong unsustainability fails to be detected if the necessary land area for absorbing carbon dioxide emissions is counted in terms of the required land area for replacing non-renewable with renewable energy resources rather than in terms of land area required for carbon capture via forestry. Since the current rate of carbon dioxide emissions is clearly in violation of SS, this puts doubt on whether EF can really provide an indicator of SS. With respect to MF, I argue that the call for general reductions in MF is economically inefficient and is not guaranteed to be ecologically effective. Because of the latter, it is also highly doubtful whether the concept of MF really provides an indicator of SS, as suggested by its proponents. If one distinguishes MF according to its potential to threaten critical functions of natural capital, then the concept of MF holds much greater promise, however. I also appraise the so-called strong environmental sustainability index, which builds on the earlier concept of sustainability gaps developed principally by Paul Ekins. While far less known and less popular than EF and MF and while facing distinct conceptual and practical problems in terms of actual measurement, I will argue that the index comes arguably closest to a real measure of SS.

The second section of Chapter 6 looks at hybrid indicators. All of these indicators are inspired by Hueting's (1980) early path-breaking work, which is briefly discussed, and they all set environmental standards for certain forms of natural capital. Two hybrid indicators – the Greened National Statistical and Modelling Procedures (GREENSTAMP) and the 'Sustainable National Income according to Hueting' – model the costs of achieving the set of environmental standards in a general equilibrium framework. This is their great advantage and disadvantage at the same time, as the modelling character makes the indicator difficult to understand as well as highly dependent on model assumptions. Though theoretically interesting, such modelling faces enormous difficulties in practice, which may explain why hybrid indicators have not taken off since the early pioneering studies developed in the late 1990s and early 2000s.

Chapter 7 provides conclusions from the main analysis. More formal derivations of basic principles and results can be found in the accompanying appendices.

NOTES

1. A more neutral term from a gender perspective would be ‘human-made’ capital. To distinguish this form of capital more clearly from ‘human’ capital, I shall refer to it as ‘man-made’ capital, however.
2. Capital is defined here broadly as a stock that provides current and future utility. For more detail, see Section 2.1, p. 8.
3. Note that throughout the book I use the terms ‘measure’ and ‘indicator’ interchangeably.
4. Value of capital should be interpreted throughout the book in real terms in the sense that the value must be adjusted for inflation.
5. The usage of the terms ‘benefits’ and ‘costs’ might at points be confusing to the reader. Whether something counts as a benefit or a cost depends on the reference point and on the perspective one takes. The benefits of preserving natural capital are the costs of depleting natural capital. Conversely, the benefits of depleting natural capital are the costs of preserving natural capital.

2. Sustainable development: conceptual, ethical, and paradigmatic foundations

This chapter will lay the foundation for the main analysis in the subsequent chapters. Section 2.1 defines the major terms used, describes the main simplifying assumptions made and the methodology that will be employed. Section 2.2 discusses a few ethical issues of SD. It provides some justification for choosing SD, discusses a time-inconsistency problem of SD, and resolves two misunderstandings about SD. Those readers who are most interested in WS versus SS itself might want to skip this section and go straight to Section 2.3, which introduces in more detail the two opposing paradigms. I explain there what their major differences are with respect to the possibilities of substituting for natural capital. Section 2.4 provides a case study on climate change, which illustrates vividly the importance of the substitutability assumption. It is argued that the conflict between those who demand drastic carbon and other greenhouse gas emission reductions and those who demand only minor reductions should really be about the substitutability of natural capital rather than about the right rate of discount.

2.1 DEFINITIONS, ASSUMPTIONS, METHODOLOGY

In this book the analysis is confined to two starkly differing *economic* paradigms of SD, namely, WS and SS. They are the most influential paradigms within debates and policy discussions about SD. Let us start with some definitions and assumptions. In some sense, SD is a vague concept – so much so that Pezzey (1992b) can present a whole gallery of differing definitions. Nevertheless, a definition most proponents of an *economic* concept of SD would be likely to accept is the following: *development is defined here to be sustainable if it does not decrease the capacity to provide non-declining per capita utility for infinity.*

For the analysis that follows, those items that form the capacity to provide utility are called capital. Capital is defined here broadly as a stock that provides current and future utility. Natural capital is then the totality of nature – non-renewable and renewable resources, ecosystems, species, and so on – that can provide human beings with material and non-material utility. It follows that those items of nature that provide disutility to human beings do not count as natural *capital*. The most conspicuous examples are viruses and bacteria that cause diseases. Man-made capital is what has traditionally been subsumed under 'capital', that is, factories, machinery, roads, infrastructure, and so on. Human capital is knowledge and human skills. Note that I use the terms 'conserving capital' and 'preserving capital' interchangeably. The same applies to the terms 'utility', 'welfare', and 'well-being'.

Obviously, the definition of SD used here is anthropocentric. Nature has value if, and only if, humans value nature. Humans might value nature for whatever reasons, however, and not merely because it contributes to the production of consumption goods and services or directly produces utility through environmental amenities. Humans might very well value nature as such and for its own sake in attributing to it 'intrinsic' value. But it is still humans who determine the value. There is no value independent of human valuation in the definition of sustainability used here.

Note that SD is defined here as development that maintains the *capacity* to provide non-declining per capita utility for infinity. In other words, it is defined in terms of maintaining the capital that is necessary to provide non-declining future utility. It is not defined in terms of non-declining utility for infinity itself. In the real world, the current generation has no control over how future generations use the capital stock they inherit, which provides them with the capacity to provide non-declining utility. One must not demand more from the current generation than it can possibly achieve. This might sound like a merely semantic distinction, but prominent environmental philosophers have similarly distinguished non-declining utility from non-declining opportunities (for example, Page 1983, p. 53; Barry 1991, p. 262). Moreover, it reminds us that people are real people with freedoms and choices, not social welfare state clients who are allocated a certain amount of utility by the omnipotent social welfare planner.

Note that my definition of SD is not utilitarian. That is, I do *not* embrace a definition of SD as '*maximised present-value* utility non-declining for infinity' which can be represented in compact form as

$$SD = argmax \int_0^\infty U(t) e^{-\rho t} dt \ \ s.t. \ \frac{dU}{dt} \geq 0 \forall t \tag{2.1}$$

where U is again (per capita) utility, ρ is the pure rate of time preference (the rate by which future utility is discounted, that is, counted less, for no other reason than being later in time), and t is time. I reject utilitarianism for my definition of SD for mainly two reasons: first, because SD is defined here in terms of maintaining the capacity to provide non-declining future utility, not in utility terms itself (see above). Second, I reject utilitarianism because I regard it to be too restrictive an assumption. Utilitarianism leaves no space for free choice: utility *must* be shifted inter-temporally so as to maximise the discounted stream of utility over infinite time (subject to the non-decline constraint). *Voluntary* sacrifices of the current generation for the sake of future generations are not allowed according to this social decision rule: the sacrifice would either increase or decrease the discounted stream of utility; in the first case, the current generation *must* make the sacrifice, in the second case, it is *forbidden* to do so.

On the other hand, utilitarianism has some advantages as well. The first is again tractability, which is one of the reasons why it is so commonly used in economics. The second is that present-value maximisation as the most common form of utilitarianism has some desirable ethical properties as well when it comes to discounting the future. Note, first of all, that the pure rate of time preference in equation (2.1) could be set to zero, as indeed many authors demand for reasons of inter-generational fairness: being later in time should be no reason for counting less (for example, Ramsey 1928; Pigou 1932; Rawls 1972; Broome 1992; Cline 1992; Azar and Sterner 1996; Stern 2007, 2014a, 2014b, 2015). If ρ is set greater than zero, then this is often called utility discounting. And yet, even with ρ set to zero there are good reasons for discounting the future within a utilitarian framework if one expects future generations to be better off than the present one. This is often called consumption or growth discounting, and it is compatible with utilitarianism since more weight is given to the present (and, by presumption, less well-off) generations. Note that this argument for discounting does not involve any bias against future generations per se. The argument for the potential ethical desirability of discounting within a utilitarian framework is formalised in Appendix 2, where the so-called Ramsey rule is derived from a dynamic optimisation model.

Clearly, my definition of SD does not give a complete social decision rule, since there are an infinite number of development paths that maintain the capacity to provide non-declining utility for infinity. It follows that there must be some decision criteria, a social welfare function in the language of economists, to choose from different paths. The utilitarian criterion is to take that path of non-declining utility which maximises the present (that is, the discounted) value. But an infinite number of other decision criteria exist, the most prominent of which are listed in Martinet (2012, pp. 49–73). My definition of SD just calls for 'maintaining the capacity to provide per capita utility non-declining for infinity' whatever the complementary social decision criterion is. Note, however, that I use a utilitarian framework at various places throughout the book in analysing WS because utilitarianism is usually embraced by proponents of WS (subject to the sustainability constraint). The same holds true for Section 2.4, p. 30, where the importance of the substitutability assumption for the case of climate change is stressed. This is because the analysis there focuses on the neoclassical cost-benefit analysis approach towards climate change, as represented by Nordhaus (1991a, 1994, 2008, 2017, 2018, 2019a), which is utilitarian.

Proponents of WS and SS have radically differing beliefs about which forms of capital are necessary for providing non-declining utility. In order to highlight this difference and to make the analysis in the book possible, I will assume for simplicity that the utility of a representative individual can sufficiently be described by a utility function of the following form:

$$U = U\left(C, Z, P\right)$$
$$\partial U / \partial C,\ \partial U / \partial Z > 0,\ \partial U / \partial P < 0 \quad (2.2)$$

where C is consumption, Z is the stock of renewable resources providing environmental amenities, and P is the stock of pollution. The first two components contribute positively to utility; hence, their partial first derivatives are positive. The last component, pollution, on the other hand, reduces utility; hence, its first derivative is negative. Note that I have split up natural capital into the stock of renewable resources and the stock of pollution, which, of course, is a capital 'bad' rather than a capital good. I have done so to keep the presentation consistent with later chapters. Nothing of substance would change if I had put Z and P together into one variable for natural capital (or rather Z and some variable for the pollution-assimilative capacity of the environment). Consumption C is to be understood broadly, including, for example, the 'consumption' of educational services. Sustainability proponents sometimes erroneously neglect that essential items of human development such as education, which enables human beings to lead an informed and self-determined life, have direct utility value, not just instrumental value in the form of investment in human capital (Anand and Sen 2000).

Why are the *stocks* of renewable resources and pollution included in the utility function rather than the resource and pollution *flows*? The reason is that if people have preferences for environmental quality, it makes sense to assume that they care about the whole stock of directly utility-relevant renewable resources and pollution and not just incremental changes to the stock, that is, flows. It has become increasingly common in the environmental economics literature to put the *stock* of natural capital into the utility function rather than the *flows* derived from the stock – see, for example, Bovenberg and Smulders (1995); Beltratti (1995); Tahvonen and Kuuluvainen (1993); and Barrett (1992).

Why are *non-renewable* resources not included in the utility function? Because non-renewable resources are important for the production of consumption goods but do (mostly) not produce any direct utility. Nobody derives direct utility from mineral and energy resources, but from renewable resources such as forests, wildlife, and so on.[1] Of course, non-renewable resources provide indirect utility via their use in the production of consumption goods and services. For the same reason, man-made capital is not included in the utility function: it (mostly) does not provide any direct utility but is a major input into the production of consumption goods and services.

Population growth is exogenous to the analysis. Whatever the size of the population, SD calls for maintaining the capacity to provide non-declining *per capita* utility. This requirement seems to be reasonable since the present generation is responsible for population growth. It can either reduce population growth or increase the capacity to provide utility to comply with the *per capita* requirement. I concede that keeping population growth exogenous to the analysis is not satisfactory. But as Solow (1986, p. 149) has put it: 'The welfare economics of an endogenously changing population is altogether murky'. Population growth makes the achievement of SD typically more difficult than if the population were stationary, as becomes clear in the measurement of WS (World Bank 2021). But note that technical progress is a force in the other direction, which is explicitly taken into account in UNEP's (2023) measure of WS, which competes with that of the World Bank. Similarly, I ignore the somewhat curious point made by Derek Parfit (1983) that, putting his 'identity problem' argument simplistically, no future generations can complain about anything the current generation does or does not do with respect to sustainability since the people who make up future generations will be different for every sustainability-relevant decision and so any particular future generations would not really be able to complain about, for example, the running down of natural capital by earlier generations since if this had not happened other people, not them, would have been born instead.

Talking of population growth: ever since I can remember, the concern has been about rising population, sometimes even framed as a population explosion. See, for example, Ehrlich (1968), though others like Julian Simon (1990, 1996) and Ester Boserup (1990) pushed against this position. And, true enough, the world population has more than doubled between 1965, when it stood at around 3.3 billion people, and 2023, when it was just above 8 billion people, according to the United Nations Population Division (https://population.un.org/wpp/). It is also true that, according to the 2024 projections by the same UN organisation, the world population is forecast to grow by another 2 billion people or so and then peak at around 10.3 billion people around the mid-2080s, only slightly falling for the rest of this century. However, it is also the case that out of the 210 countries and country-like entities for which data exist on their fertility rate in 2022, the majority (112 countries) had rates below 2.1, which is the population replacement rate that would keep populations stable in the long run (World Bank 2024). Importantly, among these are most of the ten currently most populous countries in the world, namely, Bangladesh, Brazil, China, India, Mexico, the Russian Federation, and the United States (US). Even Indonesia is practically at the replacement rate with its 2022 fertility rate at 2.15, leaving only Pakistan at a rate of 3.4 and Nigeria with a rate of 5.1 from this group as countries with relatively high fertility rates. It is only because of time lags that this trend in fertility rates decreasing below replacement rate does not yet result in population shrinking at the global level though populations in many countries that have very low fertility rates, and have had these for some time, are already shrinking. I predict that very soon unsustainably low fertility rates and population ageing and shrinking rather than population growth will dominate the debates. And whereas we know exactly how to bring down population growth (for example, by investment in education of girls, improved post-natal health care, functioning pension schemes), no one has yet figured out how to bring fertility rates up beyond marginal increases that typically fall far short of bringing them back up to the replacement rate of 2.1. Conservative governments in Hungary, Poland, and Russia have failed with their anti-feminist policies oriented towards traditional family values where women stay at home and bear and raise children (Cook et al. 2023), as has South Korea with its policies of financially incentivising childbearing in the face of its ultra-low fertility rate of 0.78 (Park 2020). My prediction is that unsustainably low fertility rates will become one of the most challenging and pressing issues of the 21st century. That the capacity to provide non-declining per capita utility should be maintained *for infinity* is more for convenience. Doing so ensures better mathematical tractability. What is actually meant by 'for infinity' is that development cannot be sustainable if it maintains the capacity to provide non-declining utility only temporarily and leads to a decline in this capacity after some finite time.

Speaking of the 'present' and 'future' generations is of course a fictitious simplification. Every day some people are born while others die, so there is a permanent flow of people into and out of the present generation, while 'future' generations are not a given but are contingent on the 'present' generation's actions. One should interpret the notions of 'present' and 'future' generations as ideal types in Max Weber's (1922) usage of the term. Therefore, they are not really existent, but they help enormously in conceptualising and analysing problems.

The analysis of this book mainly looks at *inter*-generational as opposed to *intra*-generational equity and fairness questions. Inter-generational equity means equity between the present and future generations, while intra-generational equity means equity within the present generation – for example, equity between the current rich and current poor people or between nation-states and their society and people of the 'Global North' (also sometimes called developed countries) and of the 'Global South' (also sometimes called developing countries). Inter-generational equity and fairness questions are at the centre of concern for most proponents of SD, but that is not a good reason to exclude intra-generational conflicts per se.[2] As Heyes and Liston-Heyes (1995, p. 3) argued back in 1995, with their argument as true now as it was back then: ‘it may be that those embroiled in the environmental sustainability debate have become so obsessed with intergenerational equity that intragenerational equity considerations have been swept under the rug’.

My justification is that I want to focus on inter-generational distributional questions here.[3] Ignoring, to a large extent, intra-generational distributional issues makes the analysis much easier. And again, this admittedly restrictive assumption ensures tractability, because then I can let different generations be represented by a representative agent of each generation. At certain points, I shall loosen this assumption somewhat, however, and ask what consequences the unequal intra-generational income distribution has on the likelihood of achieving sustainability. This will be the case, for example, in Section 2.4, p. 30, on climate change and in Section 4.5, p. 121, on the opportunity costs of preserving natural capital. Also, in Neumayer (2011) I discuss the links between inter- and intra-generational equity issues in detail.

The methodology I am using is that of the boundedly rational individual who attempts to maximise his or her utility. This methodology is usually called the economic paradigm, although it is debatable whether there can be anything like *the* economic paradigm when economists themselves disagree about the specifics of ‘their’ paradigm. I want to put emphasis on the word *boundedly*. I am interested in real-world problems, and I do not want to dispose of those problems by simply assuming them away. Hence, I do not assume the presence of either perfect information, perfect foresight, or boundless computational capacity, none of which exist in actual reality. For a good case for this view on ‘rationality’, see Simon (1982).

The motivation for choosing the economic paradigm as a methodology is not that I am convinced it reflects actual human behaviour at all times and to all extents correctly. Far from it: there is much more to human life than being a rational utility maximiser, and there is plenty of evidence from several social sciences, including behavioural economics and psychology, demonstrating just how little actual human behaviour converges to the rational utility-maximising postulate (Kahneman 2011). But there is no better alternative to the economic paradigm, especially so if one is looking for something tractable. The main reason for sticking to the economic methodology is a different one, however: I want to grant the paradigms of sustainability I am looking at the most favourable conditions, especially because of my primary interest in exploring their limits. Since I am looking at economic paradigms of sustainability, it seems only fair to analyse them according to their own standards. It is all too easy to dismiss a paradigm as pure nonsense from a perspective outside the discipline.

I am taking WS and SS seriously as economic paradigms, but I can only do so by basing my analysis on the economic methodology.

In Section 2.2, p. 16, I present some arguments for why it is justifiable to pursue SD. After that, it will simply be assumed that the ethical decision to strive for SD, as defined here, has already been taken. I assume that policymakers act in accordance with the SD goal without pursuing any other interest that would contradict this aim; that is, they are credibly committed to SD. In terms of political economy, this assumption is utterly naive, of course. It fits nicely into the analysis here, however, which is essentially about exploring the limits of the two paradigms of sustainability as if they were the central goal for policymakers.

What about consumer sovereignty? It is a central value for many economists, but it can only refer to the sovereignty of the present generation's consumers since future generations are not present today and cannot reveal their preferences in today's markets. Of course, with overlapping generations and parents who are somewhat altruistic towards their offspring, there exists some protection for the welfare of future generations. Indeed, depending on how exactly parents value the welfare of their offspring, SD might not clash with consumer sovereignty. But, in general, there is no guarantee that private parental altruism will lead to sustainable or socially optimal outcomes, both because this parental altruism might very well be of insufficient reach and because the welfare of future generations has to a certain extent the characteristics of a public good since what is beneficial for my own children often will be beneficial to others as well.[4] Hence, consumer sovereignty could well conflict with SD. I assume here, however, that either consumers also act in accordance with the SD goal or – in case of conflict – that consumer sovereignty is overridden by policymakers.

This, of course, leaves open the question of why consumers would vote for policymakers who override their preferences. However, I am assuming away any problems of political economy in order to focus on my central research questions which presuppose that society is committed to SD. In this sense, the danger of 'some tyranny of decision-making in the name of sustainability' (Pearce 1998, p. 48) is excluded in my analysis *by assumption*. Again, this is in the interest of exploring the limits of both paradigms.

In some instances, I shall present mathematical equations or models to prove a point or for reasons of analytical rigour. These will mainly be simple models, and I shall always explain the intuition behind the models presented. It is of great importance to me that I write clearly and concisely in a manner that is understandable not only by trained economists but also by everybody interested in SD with some basic knowledge of economics.

2.2 THE ETHICS OF SUSTAINABLE DEVELOPMENT

Why is it that – past concern about the welfare of coming generations notwithstanding – scrutinising the consequences of economic activity on the capacity for generating future utility has only relatively recently become an explicit academic enterprise? The answer is that it is only now that humankind itself *and* its economic activity have reached a scale that is potentially big enough to threaten the welfare prospects of future generations. The combination of the exponential rise in human numbers and the exponential rise in economic activity, which has resulted in tremendous natural resource extraction, environmental destruction, and other natural capital degradation, especially over the last couple of centuries, is unprecedented in human history. Also, human activity has now reached a scale that is capable of potentially endangering human survival as we know it and have become used to. Climate change is an example that shows that the uncertainties mankind has to cope with have vastly increased (IPCC 2021).

But this fact alone is not enough to make a case for SD. Ethical principles – and the aim to maintain the capacity to provide non-declining per capita utility forever is such a principle – never follow from facts alone. Hence, this section briefly discusses the ethics of SD before the following main chapters take the commitment to SD for granted. Section 2.2.1 presents arguments for committing to SD. Section 2.2.2 discusses a kind of time-inconsistency problem of SD, that is, the incentive problems that arise from the hazard that future generations might deviate from SD. Section 2.2.3 resolves two misunderstandings about what SD requires and clears the way for the main analysis in later chapters.

2.2.1 Reasons for Committing to Sustainable Development

Before providing some arguments to derive SD as an ethical principle, let me first make explicit what everybody understands intuitively: Why is it that the welfare of future generations cannot simply be left to their own care? The answer is, of course, that their very existence and the conditions of their existence are dependent on the present generation's actions. Future generations are 'downstream in time' so to speak and are therefore vulnerable to the choices made 'upstream in time'. This vulnerability is exacerbated by the fact that future generations, almost by definition, are not present in today's market and political decisions, and they have no present voice, vote, or market power. However, the fundamental asymmetry between the present and the future really cuts both ways: everything the present does can affect the future; nothing that the future does can affect the present anymore. Harm that is undertaken now cannot as such be undone in the future, but equally, present sacrifices for the benefit of the future cannot be compensated for by the future because, by that time, the present generation will no longer be around. This fundamental asymmetry puts the present generation into a strong position of dominance: it is an inter-temporal dictator, not even by its own choice, but simply because the flow of time is unidirectional and cannot be reversed. A natural and somewhat seductive question is then: Why not exploit this unequal position and maximise our own utility without any concern for the future? 'Après nous le déluge?' Indeed, why not?

One answer could be that since people have children, this shows their concern for the future. The problem with this argument is that not all people have children, that some who do treat them rather badly, and that while people might care about their own children, grandchildren, and great-grandchildren maybe, as soon as we consider the distant future, things have become so diffuse and remote that nobody could claim direct kinship relations anymore. Immediate offspring concern does not reach as far as the consequences of our economic activity do – climate change being a case in point.

More generally, the fact that people have children does not answer the question of *why* we should care for the future. As I said, normative principles do not follow from facts. So let us come up with a normative argument. Maybe we should care for the future because it is right or just to do so. But not a lot has been gained therewith, the question then being why is concern for the future right or just?

One possible answer was given by Immanuel Kant's deontological moral theory, which found its most widely known expression in his categorical imperative: 'Act only according to that maxim by which you can at the same time will that it should become a universal law' (Kant 1785 [1968], p. 51, my translation). Following this imperative, we should not only care for the future as such but even espouse the principle of maintaining the capacity to provide non-declining future utility. This is because we could not wish that any other principle should become a universal law since this would imply that we possibly would have been worse off due to decisions of others in the past, which is not in our own interest.

However, the next question is then, 'Why should we follow the categorical imperative?' As with all moral principles, there can be no conclusive, definitive answer that could not be questioned for some reason or other. Nevertheless, a good argument for following the categorical imperative can be made by applying the 'veil of ignorance' of John Rawls's (1972) *A Theory of Justice*.[5] According to Rawls, moral principles are considered just or fair if they could be chosen by a representative rational individual in an 'original position' behind a virtual veil of ignorance concerning his or her future position both in time and space and his or her social position in society.[6] They are considered fair precisely because, due to this ignorance, the representative individual cannot construct principles that are directly designed to further his or her own advantage. What is important for our analysis here is that the representative individual would not know which generation he or she would belong to. Hence, accepting the categorical imperative as a moral norm, and the principle of sustainability following therefrom, could be said to lie in the best self-interest of the individual: if I do not know which generation I shall belong to, then the categorical imperative and the principle that no generation is allowed to gain at the expense of future generations could be said to protect my interests best.[7]

Note, however, that the imperative does not follow compellingly from the original position. If the representative individual behind the veil of ignorance exhibited strong risk preference, he or she might be willing to accept a 'first come, first served' rule in which the first generations are allowed to improve their own lot at the expense of the welfare and, indeed, the existence of, later generations, in the hope that he or she would end up in an earlier generation. On the other hand, the acceptance of the categorical imperative does not depend on extreme risk averseness, as the 'maximin' or 'difference' principle does, which Rawls himself derived from his theory of the original position.[8] For more on the distinction between the principle of sustainability and the maximin principle, see Section 2.2.3.1, p. 19.

To summarise, arguments derived from Kant's deontological moral philosophy and from a Rawlsian 'original position' point of view can make SD plausible as an ethical choice. Of course, many ethical issues have not been discussed here (such as Parfit's [1983] 'non-identity problem'). But this book is in general not about moral philosophy. The limited purpose of this small section was to give a start-up motivation for committing to SD and to show that the principle of sustainability is not an implausible moral norm for intergenerational decision-making.

2.2.2 The Time-Inconsistency Problem of Sustainable Development

In this section, a problem is highlighted that is rarely recognised in the literature on SD. The problem is as follows: assume that the present generation commits itself to SD, that is, commits itself to maintaining the capacity to provide non-declining per capita utility *into the indefinite future*. Obviously, it can only control the present, but not the indefinite future. It can make present sacrifices that it expects not to contradict SD, but it cannot force the next generation, and the next after the next, and so on to commit themselves to SD. There is a time-inconsistency problem here: the present generation would like, but is unable to bind all coming generations to its own ethical choice for SD. Some future generation might well find it attractive to deviate from SD or to abandon it completely. But this possibility has severe repercussions on the incentives for the current generation to opt for SD in the first instance: What is the point in making present sacrifices if the benefits of those sacrifices that were thought to benefit all future generations can be reaped by some single future generation that opts out from SD?

There is no easy solution to the fundamental time-inconsistency problem of SD. At the end of the day, the only thing the current generation can do is influence coming generations such that they regard their enduring commitment to SD as the 'right' decision to take. The current generation cannot influence very distant generations directly, but it can influence the next generation through education. If each generation influences its offspring to regard SD as a desirable goal, then the problem of time-inconsistency could be overcome. Admittedly, there is no guarantee that future generations will stick to SD, but the current generation might well be sufficiently convinced that they feel undeterred from incurring costs for the benefit of the future due to the still existing possibilities that their efforts will be frustrated by coming generations.

2.2.3 Two Misunderstandings about Sustainable Development Resolved

There are two main misunderstandings about SD that should be corrected at the beginning of this analysis because, if they were valid claims, the justification for the book would be severely put into doubt.

2.2.3.1 'SD might lock society into eternal poverty'

The first one is that sticking to SD will lock society into eternal poverty if it is poorly endowed at the start. Solow (1974a) developed this concern when he examined how applying Rawls's (1972) maximin rule to the inter-generational problem of the optimal depletion of a given stock of a non-renewable resource and the accumulation of man-made capital would affect current and future utility. Richter (1994, p. 46) and Dasgupta (1994, p. 35) have raised similar concerns. I shall not reproduce Solow's model since his proposition is easy to understand intuitively. The argument is as follows:

1. The maximin rule means that the utility of the worst-off generation has to be maximised.
2. It follows that utility has to be constant throughout time, that is, utility has to be equal for all generations. Why? Imagine otherwise: some generation has higher utility than other generations. But then the maximin criterion would call for shifting utility away from this generation to others who are worse off. The same applies vice versa if some generation has lower utility than other generations. Only, this time, utility has to be shifted towards

this generation. Equilibrium and compliance with the maximin rule is where all generations have equal utility. Hence utility has to be constant throughout time. (In Solow's model, utility can be shifted to and from generations simply by allocating more or less of the available stock of the non-renewable resource to them.)

3. It follows that the initial generation cannot be asked for even the smallest sacrifice in the consumption of their share of the resource that would allow investment in man-made capital and an accumulation of this form of capital over time because that would make it worse off than future generations. Hence, if the initial situation is such that society is poor, humankind will be locked into poverty throughout time.[9] That is, the welfare properties of the maximin criterion depend very much on 'the mercy of the initial conditions' (Solow 1974a, p. 33).

If the argument were valid, then it would establish a huge rebuff for the SD case because society would be required to stick to constant utility when it might have had rising utility throughout time due to the accumulation of man-made capital if only some initial small sacrifice were made. It would be rather difficult then to do justice both to the present and to future generations. Fortunately, the argument is based on a misunderstanding of SD.

There are two possible ways to show this. The rather pragmatic counterargument says that humankind is now in a situation that is no longer characterised by an initial lack of wealth. That earlier generations have made sacrifices for us we cannot change anymore. It is futile to imagine how poor we would still be had earlier generations already applied the maximin criterion. Now that we are no longer poor, applying the maximin criterion does not lock future generations into eternal poverty. Dasgupta and Heal (1979, p. 311) seem to endorse this argument for rich countries. But one of the problems with this line of thought is just that: it does not apply to poor countries and arguably most of the developing countries are still poor by any measure. Another problem is that it still locks society into a constant utility time path, although maybe from a higher initial level of utility.

Fortunately, the second counterargument does not depend on the present generation being rich and refutes the supposition that sustainability locks society into a constant path of utility over time. It simply says that SD neither is equivalent to nor implies the maximin criterion: SD is *not* calling for constant or equal utility, but for maintaining the capacity to provide non-declining utility. This might appear as a minor difference in the choice of words, but it produces a huge difference in its ethical prescriptions. For SD, properly interpreted, allows earlier generations to make *voluntary* sacrifices in order that coming generations can enjoy higher utility, whereas the maximin criterion does not. In some sense, this counterargument turns the debate over SD from its head back to its feet. The 'locked into eternal poverty' argument sprang from concern over the present generation's utility, whereas SD was genuinely developed out of concern for the utility of future generations. No proponent of SD ever denied the present generation the right to make *voluntary* sacrifices for the future (nor, to be fair, did Solow do so; he was only exploring the consequences of applying the maximin criterion). SD rules out 'mortgaging the future', so to speak, but it does not rule out bequeathing a better world. On the other hand, nor does SD *require* to bequeath a *better* world. Barry's (1991, p. 267) claim that:

> … if one believes that successive generations made sacrifices in the (no doubt vague) expectation that each generation would pass on more than it inherited, this would constitute a prima facie case for saying that the present generation has a certain obligation to continue with this process …

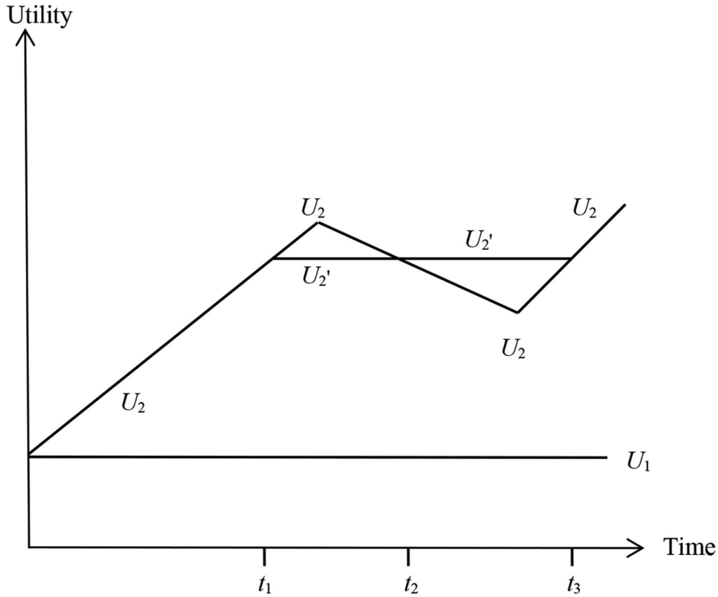
is not backed by the principle of sustainability. SD, as defined here, only calls for *maintaining* the capacity to provide non-declining future utility.

A different, and still unresolved, question is whether the obligation to some future generation changes if an earlier generation deviated from the principle of sustainability – see the discussion of the time-inconsistency problem in Section 2.2.2, p. 18. Does this generation have to compensate for the deviation of the past, or does it simply have to maintain the now lower capacity to provide non-declining utility? Strictly speaking, sustainability would only require the latter, but compensation might be expected if the costs of doing so are low. There really is no general answer to this question, however.

2.2.3.2 'SD demands the choice of greatly inferior utility paths'

A similar argument to that made in Section 2.2.3.1 holds that SD requires society to prefer very low constant utility paths to a persistently rising path that has a temporary very small decline in utility somewhere along the path. Remember from Section 2.1, p. 8, that SD was not defined in direct utility terms, but in terms of maintaining the capacity to provide non-declining future welfare. Nonetheless, for the sake of refuting the argument, assume that a society committed to SD could directly choose a utility path over time and assume for simplicity that there are only two utility paths which society could choose from: U_1 provides constant utility forever, U_2 provides higher utility than U_1 everywhere, but with a temporary dip along the path.

Look at Figure 2.1 which is taken from Pezzey (1995, p. 4) with amendments. The argument asserts that SD requires that U_1 is preferred over U_2. Beckerman (1994, p. 196) therefore concludes that sticking to SD would force society to choose greatly inferior utility paths. Again, if the argument were



Source: From Pezzey (1995, p.4).

Figure 2.1 *Non-declining versus constant utility*

valid, it would present a huge rebuff against the case for SD. Fortunately, it is not valid.

The counterargument runs as follows: if the economy is 'productive' in the sense that saving a share of current income for investment leads to a net increase in future utility (Pezzey 1995, p. 12), then the utility path with the temporary decline in utility can be modified into a path that is non-declining along the whole path by saving a certain amount before the decline is supposed to occur and then using those savings later on to prevent the decline. Referring to Figure 2.1, ensuring sustainability would mean starting 'extra-saving' from time t_1 to t_2 and using these 'extra-savings' to prevent a decline in utility from time t_2 to t_3. That is, from t_1 to t_3 society deviates from U_2 to follow the utility path U'_2, after t_3 society returns to the original path U_2.

The assumption that the economy is 'productive' is not very restrictive, so applying SD does not force society to choose greatly inferior utility paths. What it does, however, is require earlier generations to save more so that later generations do not have to experience a decline in utility. Hence, the earlier generations' utility does not rise as much if the sustainability constraint is binding as it would without the constraint. But, then again, this is what SD is all about.

2.3 WEAK VERSUS STRONG SUSTAINABILITY

In Section 2.1, p. 8, SD was defined as development that does not decrease the capacity to provide non-declining per capita utility for infinity. But what does that mean and how is it to be ensured? This, of course, is the point of divergence, and it opens fundamental disagreements that are not to be confused with semantic disputes about the meaning of the term. SD is a contestable concept and there is a real struggle over its interpretation in practice.

In this section, the two opposing paradigms of sustainability relevant to the analysis are presented. Their main difference derives from starkly contrasting assumptions about the substitutability of natural capital. I call WS the substitutability paradigm, whereas SS can be perceived as the non-substitutability paradigm. Section 2.3.1 presents WS, and Section 2.3.2 presents SS. The distinction between WS and SS should presumably be credited to Pearce et al. (1989). Interestingly, of the two major international agencies devoted to development, one (the World Bank) started out as a proponent of WS (World Bank 1992, 2002), but seems to have been converted to the SS camp, at least as far as climate change is concerned (World Bank 2009), while the other (the United Nations Development Programme [UNDP]) started out uncommitted (UNDP 1992, 1994), but seems to have tended towards an SS view earlier than the World Bank (UNDP 1998, 2006, 2007).

2.3.1 The Paradigm of Weak Sustainability

WS is often called ‘Solow–Hartwick sustainability’ (for example, by Gutes 1996, p. 150) because it is based on the work of Nobel Prize winner Robert Solow (1974a, 1974c, 1986, 1993a, 1993b) and John Hartwick (1977, 1978a, 1978b, 1990, 1993). WS requires keeping *total net investment*, suitably defined to encompass all relevant forms of capital, above zero. This can be interpreted as a generalisation and extension of the so-called *Hartwick rule* (Hartwick 1977). WS is built on the assumption of substitutability of natural capital (as well as any other form of capital). Because of this assumption, I call WS the ‘substitutability paradigm’. Hence, its investment rule, while covering all relevant forms of capital, need not distinguish between specific forms of capital. If investment in man-made and human capital is big enough to compensate for the depreciation of natural capital, an explicit policy of sustainable development is not even necessary, for then sustainability is guaranteed quasi-automatically.[10] If not, apply suitable measures (for example, a resource tax, saving subsidy, or environmental regulation) to keep total net investment above zero (Mikesell 1994, p. 85).

Note that usually the relevant literature speaks of savings rather than investment and uses the term 'genuine savings' (GS), a term introduced by Hamilton (1994), for total net investment. To add to the confusion, the World Bank used the term 'net adjusted savings' to refer to genuine savings in its flagship statistical publication *World Development Indicators*. In my view, which is shared by Dasgupta (2001b) and Arrow et al. (2004, 2007), genuine investment would be a better term to use than genuine savings. The reason is that in macroeconomics, savings are often defined as private savings. For example, in a closed economy, private savings is equal to investment plus government expenditures minus taxes. Savings in the usage of genuine savings instead refers to the sum of private and public savings (taxes minus government expenditures), which generates the equality between total savings and investment. For the rest of this book, I shall speak of genuine savings instead of investment to maintain harmony with the usage of terms in most of the relevant literature.

WS is built upon the assumption that natural capital is either abundant or substitutable both as an input into the production of consumption goods and services and as a provider of direct utility. This means that natural capital can be safely run down so long as enough man-made and human capital is built up in exchange. In the words of Solow: 'Earlier generations are entitled to draw down the pool (optimally, of course!) so long as they add (optimally, of course!) to the stock of reproducible capital' (Solow 1974a, p. 41).

With respect to natural capital as an input into the production of consumption goods, proponents of WS hold that:

- natural resources are super-abundant;
- or the elasticity of substituting man-made capital for resources in the production function is equal to or greater than unity, even in the limit of extremely high output–resource ratios;
- or technical progress can overcome any resource constraints.

Quite clearly, given the assumptions about the availability of natural resources and possibilities for substitution of natural capital in the production of consumption goods and services, WS is a paradigm of resource optimism – see Section 3.2, p. 54. As regards natural capital as a provider of direct utility, the reader might be uncomfortable with the proposition that the components in the utility function are substitutes for each other. It means that a rise in consumption (C) can compensate future generations for a decline in the stock of renewable resources (Z) or a rise in the pollution stock (P). It is important to note, therefore, that WS holds that there are good reasons to presume that with rising incomes and hence rising *C*, *Z* will *eventually* rise as well, and *P* will *eventually* fall. That is, WS holds that economic growth or a rise in consumption (*C*) will eventually be good for the environment as well. Because the proponents of WS believe that, eventually, with rising incomes the state of the environment will improve as well, I call them environmental optimists – see Section 3.3, p. 82.

Note that although WS is deeply rooted within neoclassical economic thinking given its assumption of substitutability of natural capital, it is still conceptually different. What makes it different are two things: first is the willingness of its proponents to take natural capital both as an input into production and as a direct source of welfare seriously and include it in their models. Second, WS differs from 'present-value maximisation', the reigning utilitarian paradigm of neoclassical welfare economics, in postulating the constraint that the capacity to provide non-declining utility must be maintained at any point in time. While Beckerman (1994) provides an excellent defence of neoclassical welfare economics, he is therefore wrong in saying that WS 'offers nothing beyond traditional welfare maximisation' (p. 191). More formally, WS in effect denies the validity of *potential* Pareto improvements in an inter-generational context and demands *actual* compensation if future generations would suffer from an action that benefits the current generation. That is, for inter-generational allocation decisions, WS rules out the validity of the so-called Hicks–Kaldor test (Hicks 1939; Kaldor 1939) that is the common decision criterion in traditional welfare economics. Present-value maximisation and sustainability can strikingly conflict with each other. Appendix 1 provides a stylised example showing that applying present-value maximisation as the decision criterion could even lead to the optimal (efficient) choice of a path that finally ends up in catastrophe, that is, to zero utility and therefore to the extinction of humankind![11] I do not claim that this stylised example is particularly realistic, but it shows that, in principle, applying present-value maximisation can lead to utmost unsustainability. As Chichilnisky (1996) has shown, the clash between present-value maximisation and sustainability holds true even for less restrictive definitions of sustainability. Her definition only rules out dictatorship of the present and the future, that is, giving no weight to the distant future or no weight to the present, but does not rule out declining utility along the path. Not surprisingly, since present-value maximisation with any positive constant discount rate gives only infinitesimally small weight to the distant future, it clashes with this definition of sustainability as well.

2.3.2 The Paradigm of Strong Sustainability

Proponents of SS are not against achieving WS. Rather, they would regard achieving WS as an important first, but insufficient, step in the right direction.

In a sense, SS encompasses WS but adds further requirements. In this perspective, WS is better than traditional neoclassical economics, but it is still a far cry from what is needed for SD.

Herman Daly's (1977 [1992a]) book *Steady-State Economics*, first published in 1977, might mark the foundation of SS. Daly, one of the founders of the International Society for Ecological Economics (ISEE), and Robert Costanza, co-founder and, until 1997, the president of the ISEE, have also been two of the most prominent proponents of SS (Daly 1991, 1977 [1992a], 1992b, 1994, 1995a, 1996, 2005; Daly and Costanza 1992). Many others have also made early contributions to the creation of the paradigm. To list just a few: Robert Goodland (for example, Goodland and Daly 1992), Roefie Hueting (for example, Hueting 1980, 2010), Richard Norgaard (for example, Norgaard 1994), John Proops (for example, Faber et al. 1992), Charles Perrings (for example, Perrings 1989), Brian Barry (for example, Barry 1991), Michael Jacobs (for example, Jacobs 1991) and Clive Spash (for example, Spash 1993). David Pearce and his colleagues have also provided arguments for stronger versions of sustainability (for example, Pearce et al. 1990; Turner and Pearce 1992) without necessarily subscribing to the paradigm of SS. The many contributions to SS render its definition somewhat more difficult than that of WS.

Despite SS being more difficult to define than WS, the essence of SS is that it regards natural capital as fundamentally non-substitutable through other forms of capital. I therefore call SS the 'non-substitutability paradigm'. There are two differing interpretations of SS in the literature. In one interpretation, SS is the paradigm that calls for preserving natural capital itself in value terms. Note that SS, in this interpretation does not demand the preservation of nature as it is. For example, SS does not require never using non-renewable resources such as coal, as Klepper and Stähler (1998, p. 489) erroneously suggest. It requires, however, reinvesting the receipts from coal mining or oil and gas extraction into the development of renewable energy sources to keep the aggregate value of the total natural resource stock constant (Hohmeyer 1992). More generally, Barbier et al. (1990) and Helm (2015) have suggested compensating depreciation of the natural capital stock with adequate shadow investment projects.

One of the problems with this definition of SS is that it does not constrain at all the substitutability within natural capital. This is clearly at odds with the spirit of SS. To put it drastically, it would be strange to assume that more man-made capital cannot substitute for a bigger hole in the ozone layer, but an increased number of whales can. Clearly, substitutability within natural capital needs to be constrained as well, which is what the second interpretation of SS achieves.

In this second interpretation, SS is not defined in value terms but calls for the preservation of the *physical* stock of those forms of natural capital that are regarded as non-substitutable (so-called critical natural capital) (see, for example, Ekins 2003; Ekins et al. 2003). Also note that this interpretation does not allow for any substitutability among different forms of 'critical' natural capital. Nor does it imply keeping nature as it is, however. Indeed, such a task would be impossible. But it calls for maintaining its functions intact. If the flows from these forms of natural capital are used, then their regenerative capacity must not be exceeded, so that their environmental function remains intact (Goodland 1995; Hueting and Reijnders 1998). Hueting and Reijnders (1998, p. 145) give the example that 'the rate of erosion of topsoil may not exceed the rate of formation of such soil due to weathering'. More generally, management rules for preserving critical natural capital would include the following (Daly 1977 [1992a], p. 256):

- Use renewable resources such that their stock does not deteriorate. That is: harvest *at maximum* the maximum sustainable yield.
- Use the environment as a sink for pollution only to the extent that its natural absorptive capacity does not deteriorate over time.
- Protect nature reserves that provide environmental amenities and recreational opportunities. 'It is very hard to imagine a good healthy life without this natural capital' (Helm 2015, p. 60). (See also Willis 2024.)

At least some of the proponents of SS are quite pessimistic about the availability of non-renewable natural resources and believe that past levels of resource depletion ('the onetime bonanza of fossil fuel consumption' Daly 1992b, p. 244) cannot be sustained into the future. As an additional requirement, they would therefore demand that the current generation compensate the future for its use of non-renewable resources with investment in replacement renewable resources that are functionally equivalent.

In Chapter 4, I shall argue that the second interpretation of SS is more plausible. There, I shall also discuss some reasons for justifying the assumption of non-substitutability. In short, the main suggested reason for non-substitutability is a combination of the following factors (see Turner and Pearce 1992, p. 7):

- We are largely uncertain and ignorant about the detrimental consequences of depleting natural capital.
- Natural capital loss often is irreversible.
- Some forms of natural capital provide basic life-support functions.
- Individuals are highly averse to losses in natural capital. A stronger suggestion would be that individuals cannot be compensated for any environmental degradation through increased consumption opportunities (Spash 1993, 2002).

To distinguish SS clearly from the substitutability assumption of WS, it will be implied for the analysis in this book that SS holds that rising consumption cannot compensate future generations for rising environmental degradation, that is, it cannot substitute for a declining stock of directly utility-relevant renewable resources and a rising stock of pollution. Such a position is often derived from a normative rights-based theory of inter-generational justice. Sen (1982, p. 346), for example, argues that 'lasting pollution is a kind of calculable oppression of the future generation', which he regards as being similar in character to torture. Consequently, Sen (1982, p. 347) rejects the idea that future generations could be compensated for 'lasting pollution' via increased material welfare:

> Even if the future generation may be richer and may enjoy a higher welfare level, and even if its marginal utility from the consumption gain is accepted to be less than the marginal welfare loss of the present generation, this may still not be accepted to be decisive for rejecting the investment when the alternative implies long-term effects of environmental pollution.

Similarly, Barry (1991, p. 264) regards environmental pollution as not amenable to compensation by doing future generations some other good, as he makes clear in drawing the following analogy:

> We will all agree that doing harm is in general not cancelled out by doing good, and conversely that doing some good does not license one to do harm provided it does not exceed the amount of good. For example, if you paid for the realignments of a dangerous highway intersection and saved an average of two lives a year, that would not mean that you could shoot one motorist per year and simply reckon on coming out ahead.

Maybe the most elaborate and explicit argument for non-compensability was put forward by Spash (1993, 1994, 2002). He makes it very clear that in his view 'compensation does not licence society to pollute, provided the damages created are less than the amount of compensation' (Spash 1993, p. 127) and postulates an 'inviolable right of future generations to be free of intergenerational environmental damages' (Spash 1993, p. 127).

Proponents of SS also tend to be pessimistic with respect to the environmental consequences of economic growth. Goodland and Daly (1992, p. 129) and Daly and Goodland (1994, p. 76), for example, define throughput growth as an increase in the capture of resources and the pollution of more sinks, while development is seen as an improvement in productivity and efficiency. Daly (1977 [1992a]) calls an economy that develops but does not grow anymore a 'steady-state economy'. Reaching a steady-state is seen as the ultimate goal: 'Sustainable development … necessarily means a radical shift from a growth economy and all it entails to a steady-state economy, certainly in the North, and eventually in the South as well' (Daly 1996, p. 31). One should note here that Daly's use of the term differs from the standard economic definition of a steady state as a 'situation in which the various quantities' of an economy 'grow at constant rates' (Barro and Sala-i-Martin 1995, p. 19).

Whereas WS could be interpreted as an extension of neoclassical economics, SS calls for a paradigmatic shift away from neoclassical environmental and resource economics towards an 'ecological economics'. Daly (1996, p. 45) demands a drastic change in 'the basic framework of our thinking' towards a vision of the macroeconomy as a subsystem of the finite ecosystem. If the macroeconomy was not envisioned as 'the whole' anymore, but as part of the larger ecosystem, the question of an optimal scale of the macroeconomy would naturally arise (Daly 1991). The scale is optimal where the benefits of a marginal increase in the macroeconomy just equal the costs. An ecological economics would pay priority attention to both the limitedness of resource input ('source') and the limitedness of the waste and pollution-absorbing capacity of the environment ('sink'). It would thus embed the economy into the bigger ecosystem and stress the constraints that are put on its growth.

> The necessary change in vision is to picture the macroeconomy as an open subsystem of the finite natural ecosystem (environment), and not as an isolated circular flow of abstract exchange value, unconstrained by mass, balance, entropy and finitude. (Daly 1996, p. 48)

> Historically, in the 'empty world' economy, manmade capital was limiting and natural capital superabundant. We have now, due to demographic and economic growth, entered the era of the 'full world' economy, in which the roles are reversed. More and more it is remaining natural capital that now plays the role of limiting factor. (Daly 1995a, p. 50)

An ecological economics would encompass neoclassical economic theory with its emphasis on an efficient *allocation* of resources but superimpose on this the criterion of a just inter-generational *distribution* and an optimal *scale* of the macroeconomy. Thus, SS would represent a higher-level paradigm in the sense of Thomas Kuhn (1962 [1996], p. 95) rather than a mutually exclusive alternative to neoclassical economic theory. We have already seen, in discussing the difference between WS and neoclassical welfare economics, that the question of a 'just' inter-generational distribution is different from an efficient allocation of resources. But so, Daly argues, is the question of an optimal scale different in kind from the optimal (efficient) allocation of resources (see also Daly et al. 2007). Daly's favourite example is that of a boat that sinks despite the load being optimally allocated on board – simply because the overall weight is too much (Daly 1991, p. 257).

The optimal scale is thought of more as a theoretical leitmotif than as a practical device, however, because 'discontinuities, thresholds, and complex webs of interdependence make a mockery of the idea that we can nicely balance smoothly increasing ecosystem costs with the diminishing marginal utility of productions at the macro level' (Daly 1996, p. 54). This has implications for how risk, uncertainty, and ignorance are dealt with – see Chapter 4.

2.4 THE IMPORTANCE OF THE SUBSTITUTABILITY ASSUMPTION: THE CASE OF CLIMATE CHANGE

In this section, I will articulate how important the assumption of substitutability is, using climate change as a case example. I perfectly understand why many want to call it 'climate breakdown', 'climate catastrophe', or at least 'climate emergency'. The science pretty much justifies their angst. I nevertheless use the more neutral terms 'climate change' or 'global warming'. The economics of climate change, as well as perceptions of what is the verdict of the mainstream economic profession on action on climate change, have dramatically changed since the publication of the Stern Review (Stern 2007), which was commissioned by the UK government, and the ensuing controversy that followed its publication. As Heal (2009, p. 18) has put it in answering his rhetorical question of what we have learned from the Stern Review and the ensuing debate: 'I think this should change the presumption that economists hold about the need for strong action on climate change from largely negative (prior to Stern) to positive'.

Before the Stern Review, the best-known cost-benefit analysis of the expected consequences of climate change was the one by William Nordhaus from Yale University – see Nordhaus (1991a, 1994), Nordhaus and Popp (1997), Nordhaus and Boyer (2000), and Nordhaus (2008). While his earlier studies found that large-scale greenhouse gas abatement was unwarranted and that only modest policy measures should be undertaken that would not prevent a substantial increase in accumulated greenhouse gases in the atmosphere, his more recent studies, such as Nordhaus (2010, 2011a, 2017, 2018, 2019a) find that considerably more stringent abatement policies are optimal. Despite this rather drastic change in Nordhaus's optimal policy recommendations, his analysis, both older and more recent, still implicitly presupposes the validity of the substitutability assumption of the paradigm of WS, as I will show in this section. His optimal policy recommendations also come nowhere near the temperature targets and consequent emissions reductions that climate scientists and economist critics of Nordhaus recommend, as readily admitted to by Nordhaus (2019a) himself.

Most of Nordhaus's initial critics have concentrated on the issue of discounting and demanded that a lower discount rate should be applied for reasons of inter-generational fairness: being later in time should be no reason for counting less (for example, Broome 1992; Cline 1992; Azar and Sterner 1996; Stern 2007). In a series of papers, Martin Weitzman (2009a, 2009b, 2009c, 2010, 2011, 2012) has argued that conventional cost-benefit analyses of climate change, of which Nordhaus's is representative, do not persuasively account for the low-probability but extreme outcome consequences of climate catastrophes. Yet other critics have questioned whether consumption growth can compensate for environmental degradation caused by climate change. In their view, discounting is not the main issue, but substitutability is: any call for aggressive emission abatement must directly attack the substitutability assumption (see, for example, Neumayer 1999b, 2007; Spash 2002; Helm 2008). One implication is that traditional cost-benefit analysis (CBA) in the form of what to economists is known as integrated-assessment modelling (IAM) is unsuitable for decision-making on climate change. While less explicitly embracing the idea of non-substitutability, economists such as Nicholas Stern, Nobel Laureate Joseph Stiglitz, and others have increasingly converged on the same view (Stern 2013, 2022; Stern and Stiglitz 2021; Stern et al. 2022).

I select climate change as a case example because its features – current economic activity has large-scale long-term future consequences on environmental amenities, food, water, ecosystems, human health, and the capacity to provide material goods – suggest it as an ideal object of study for questions of sustainability. The major impacts of climate change will not be felt for some decades or even longer (IPCC 2021). That is, climate change will mainly impact future generations but less so the current one. Hence, the benefits of abating greenhouse gas emissions will be mainly enjoyed by future generations, while the costs of abating greenhouse emissions would have to be borne already by the current generation. Much of what will be said here could similarly be applied to other global long-term environmental problems, however, such as biodiversity loss and the problem of radioactivity caused by nuclear waste.

Discussing climate change is no easy task: the science and economics of climate change are very complex (see IPCC 2021, 2022a, 2022b), there are numerous highly technical models for CBA, and there is a vast and continually growing literature discussing the pros and cons of controlling CO_2 and other greenhouse gas emissions.[12] Quite clearly, I cannot and do not want to discuss all the details of this debate. I shall restrict my discussion to the CBA of the models of William Nordhaus (1991a, 1994, 2008, 2010, 2011a, 2017, 2018, 2019a) as well as the controversies around them. After all, it is he who was awarded the Nobel Memorial Prize for Economics in 2018 'for integrating climate change into long-run macroeconomic analysis'.[13]

2.4.1 The Nordhaus Approach towards Climate Change

Nordhaus's DICE model – the Dynamic Integrated Model of Climate and the Economy – is a dynamic optimisation economic growth model based on Ramsey (1928) in which a social planner maximises the integrated present value sum of the utility of per capita consumption. Output is produced by a constant returns to scale Cobb–Douglas production function. Output production generates CO_2 emissions which lead to climate change which leads, in turn, to losses in output. The DICE model and its recommended optimal policies have evolved over time, as explained succinctly in Nordhaus (2018, 2019a). Over successive iterations, his models have recommended relatively more stringent emission cuts. The emphasis is on 'relatively' as the optimal policy recommendations still fall far short of what the vast majority of climate scientists, many economist critics of Nordhaus and indeed the UN Framework Convention on Climate Change (UNFCCC) call for. Here is Nordhaus (2019a, p. 2002) in his own words: 'Another finding, much more controversial, is that the cost-benefit optimum rises to over 3ºC in 2100 – much higher than the international policy targets. Even with the much more pessimistic alternative damage function, the temperature path rises to 3ºC in 2100'.

Compare this to the pledge by the 21st Conference of Parties (COP21) of the UNFCC in 2015 in Paris to keep the increase in global average temperature to well below 2ºC above pre-industrial levels and to pursue efforts to limit the increase in global average temperature to within 1.5ºC.[14] Of course, it is easy to pledge something but much harder to deliver on it. Between February 2023 and January 2024, the world already experienced temperatures above 1.5ºC of pre-industrial levels and while this particular year may have been somewhat unusual and temperature rises further reinforced by a particularly strong El Niño phenomenon, the 1.5ºC will soon be breached even in longer-term average trends over multiple years. Rapid sea surface temperature rises could also signal a structural break and even faster global warming than hitherto expected given predicted concentrations of greenhouse gas emissions in the atmosphere.[15] The future is hard to predict but my own pessimistic assessment is that actual temperature increases this century may well exceed not only the Paris Agreement targets but even Nordhaus's cost-benefit optimum of 3ºC. This prediction has been corroborated by the 2024 UNEP Emissions Gap Report (UNEP 2024c).

Nordhaus implicitly accepts the validity of the substitutability assumption, which is at the heart of the paradigm of WS. He does so in two closely related ways. First, all benefits and costs are linearly added and computed as shares of total output – regardless of whether they are connected to natural capital loss or not. The only costs due to climate change are costs in the form of output losses. Note that Nordhaus does not simply ignore environmental amenities and other natural capital losses. Indeed, in Nordhaus (2008, p. 34) he states explicitly that 'consumption should be viewed broadly to include not only food and shelter but also nonmarket environmental amenities and services'. However, substitutability amongst these items is not restricted (Sterner and Persson 2008). This is valid only if future generations do not care about whether, say, the costs of climate change are connected to environmental amenities that provide them with direct utility or restrain their capacity to consume material goods.

Second, Nordhaus presumes substitutability in the way he discounts the future. His formula for discounting is the so-called Ramsey formula, which is formally derived and discussed in Appendix 2. The formula is as follows:

$$r = \rho + \eta(C) \cdot \frac{\dot{C}}{C} \tag{2.3}$$

The social discount rate *r* should be equal to the sum of the pure rate of time preference ρ and the product of the elasticity of the marginal utility of consumption $\eta(C)$ and the per capita growth rate of consumption $\dot{C}/C$. If $\rho > 0$, this is called (pure) utility discounting though Nordhaus (2019a, p. 2004) calls ρ the 'generational discount rate'. Nordhaus (1994, p. 123) calls discounting, because $\eta(C)\dot{C}/C > 0$, 'growth discounting' or, as in Nordhaus (2019a, p. 2004), 'a discount rate on goods'.

Nordhaus does not base the discount rate he chooses on ethical principles (which would follow the so-called prescriptive approach) but calibrates the individual components of the Ramsey formula to be such that they fit his estimate of actual, observed real rates of return on capital and savings rates (so-called descriptive approach towards discounting). This distinction is very important and makes Nordhaus's analysis radically different from the one provided in the Stern Review (Stern 2007), as I will show below.

How does Nordhaus arrive at the discount rate he uses in his analyses? The specific discount rate he uses has undergone several modifications throughout the years. However, these changes relate more to the individual components of the Ramsey formula, rather than the resulting overall figure for a discount rate, which has, however, also been slightly lowered over time. Nordhaus (1994, p. 11) sets the pure rate of time preference, ρ, equal to a constant rate of 3 per cent. In Nordhaus and Boyer (2000, p. 16), the pure rate of time preference is assumed to decrease slightly to 2.3 per cent in 2100 and 1.8 per cent in 2200 'because of the assumption of declining impatience', which is not further motivated, however. Nordhaus (1994, pp. 11ff.) assumes a logarithmic utility function for which $\eta(C)$ is equal to 1 and projects global $\dot{C}/C$ to be about 3 per cent in the first few years, declining slowly in later decades (Nordhaus 1994, p. 125). Hence, his overall discount rate is approximately 6 per cent to start with. In Nordhaus (2008), he lowers the pure rate of social time preference from 3 per cent to 1.5 per cent. As this would, *ceteris paribus*, generate a lower discount rate than what he regards as the real rate of return on capital, he recalibrates the utility function to match this real rate of return, which prompts him to use a value of $\eta(C)$ equal to 2. His estimate of future global consumption growth is also somewhat lower at an average of around 1.9 per cent in the first half century of projections. Together, this gives a discount rate of around 5.5 per cent for the first half century of projections, which he regards as a good, conservative estimate of the real rate of return on capital. In Nordhaus (2011a), he keeps the pure rate of social time preference at 1.5 per cent but lowers the value of $\eta(C)$ to 1.5. Together with projected growth in consumption, this results in discount rates of around 5 per cent for 2005–2055 and 4.2 per cent over the longer time period of 2005–2105. In other words, because of the presumed slowing of consumption growth, the discount rate also slightly declines over time. In Nordhaus (2019a, p. 2005), he postulates: 'The descriptive approach yields a market rate of return in the neighborhood of 5 per cent per year when risks are appropriately included'.

Whatever the specific values that enter the Ramsey formula, the underlying assumption in Nordhaus's analyses is substitutability of natural capital. To see why, recall the ethical rationale for the inclusion of $\eta(C)\dot{C}/C$ in the Ramsey formula: given that $\eta(C)\dot{C}/C > 0$, the future should count less because it is then presumed to be *better off* due to the increase in consumption (weighted by the elasticity of the marginal utility of consumption). That is, future losses arising from climate change, for example, in the form of environmental amenities, are implicitly assumed to be compensable by an increase in other consumption goods. Natural and other forms of capital are substitutes.

One might think that if the current generation were committed to WS, this would demand higher emission abatement than found by Nordhaus since he does not explicitly take WS as a side constraint to his CBA. This is not the case, however. Solely judged from the requirements of WS, it is most likely that no explicit abatement policy whatsoever is warranted! The reason is that if natural capital is substitutable, then the very large projected increase in per capita income implies that future generations are likely to be materially much better off than the current generation due to investments in man-made and human capital, and there is no need to combat climate change for reasons of WS – given the validity of the substitutability paradigm. Why does Nordhaus then come to the conclusion that some emission reductions are optimal? The answer is that Nordhaus endorses a utilitarian framework in which it so happens that even though the future is better off than the present, the current generation is still called upon to provide some sacrifices, which make it still worse off in comparison to the future. This will be the case if the future benefits after discounting are higher than the present costs of sacrifice that bring the future benefits into effect. In this sense, Nordhaus's computations are more friendly to future generations than a mere commitment to WS would be. Note, however, that WS should be regarded as traditional neoclassical welfare economics plus the *additional* requirement to maintain the capacity to provide non-declining welfare over time. Thus interpreted, WS would come to the same conclusion as Nordhaus does.

2.4.2 Critique of the Nordhaus Approach (I): Discounting the Future

Many aspects of the Nordhaus approach have been criticised (Ayres and Walter 1991; Tol 1994; Chapman et al. 1995; Price 1995; Cline 1996; Ekins 1996; Howarth 1996; Sterner and Persson 2008; Weitzman 2009a, 2009b, 2009c, 2010, 2011, 2012, 2013, 2014; Dietz and Stern 2015; Howard and Sterner 2017; Wagner and Weitzman 2018; Grubb et al. 2021; Van der Wijst et al. 2023). I shall concentrate here on the three most important criticisms, to be dealt with in separate subsections: the rate of discount used to value future costs and benefits, deep structural uncertainty with respect to catastrophic climate change outcomes, and the issue of substitutability of natural capital. I shall argue that the likely non-substitutability of natural capital loss inflicted by climate change provides the most persuasive criticism of Nordhaus's approach.

Most critics of Nordhaus have focused on the discount rate chosen. Lowering the applied discount rate would drastically increase the warranted emission abatement, as confirmed by studies of Cline (1992), Fankhauser (1994), Chapman et al. (1995), Stern (2007), as well as Nordhaus himself (2011a, 2019a). Nordhaus (2019a, p. 2005) regards discounting as 'perhaps the most important issue facing current climate policy'. The reason why a lower discount rate dramatically changes the optimal policy recommendation of a CBA of climate change is easy to understand: the costs of climate change are heavily skewed towards the distant future, whereas the costs of emission reductions are heavily skewed towards the present and near future. The lower the discount rate, the more the long-term damages of climate change count in present-value terms relative to the more near-term abatement costs.

As mentioned already, Nordhaus follows a descriptive approach towards discounting: the discount rate applied to climate change economics should mirror the real rate of return on capital. The descriptive approach can be justified on efficiency grounds. Efficiency requires that investments should be evaluated at their opportunity cost. If investments generate a 4–5 per cent real rate of return, then investments in climate change policies must generate the same rate of return to be considered optimal. Using a different, say lower, rate would channel scarce resources away from investments that provide the future with a higher real rate of return.

Let us now turn to the critique of Nordhaus's approach towards discounting. Dietz and Stern (2008) argue that to look for market rates of return as guidance on the choice of social discount rate used for decision-making on climate change is misguided. Their reason is that market rates are not socially optimal rates and that it is not clear what rates to use for the case of climate change, given that there is very little market information for investments concerning the very long run. In other words, Dietz and Stern (2008) argue that even if one wanted to follow the descriptive approach, it is not clear that this would necessarily lead to the high discount rates used by Nordhaus.

Moreover, many economists and philosophers have long since demanded that when it comes to long-term decision-making, the discount rate should be set on ethical grounds, following the prescriptive instead of the descriptive approach. They have also typically demanded to set the pure rate of time preference equal to zero for reasons of inter-generational fairness: being later in time should as such be no reason for counting less (for example, Ramsey 1928; Pigou 1932; Rawls 1972; Broome 1992; Cline 1992; Azar and Sterner 1996; Stern 2007, 2014a, 2014b, 2015). The main argument is that future generations are excluded from today's market and political decisions (for example, Broome 1992, pp. 89ff.). If future generations could reveal their preferences, they would surely opt for higher investments for the benefit of the future, thus driving down the real rate of return on investment. Since we cannot know counterfactually what the real rate of return on investment would be if future generations were not excluded from today's market and political decisions, it can be said to be fair to set the pure rate of time preference equal to zero: being later in time should be no reason for counting less.

Going beyond the issue of the pure rate of time preference, Azar and Sterner (1996, pp. 177ff.) have further abandoned the assumption of a worldwide representative consumer and have examined the consequences of *intra*-generational unequal distribution. They argue as follows: if it is right to apply the Ramsey formula to future generations and ask what their marginal utility of rising consumption is, then it must also be right to take into account the marginal utility of the much poorer people in the present-day and future developing world. It was taken as a justification for discounting that future generations are expected to be better off in Ramsey's formula. For the same reason, Azar and Sterner (p. 178) argue 'that a given … cost which affects a poor person (in a poor country) *should be valued as a higher welfare cost than an equivalent cost affecting an average OECD citizen*'. Because the costs of climate change are relatively higher in developing countries than in developed countries due to their greater vulnerability and their more restricted capacity for adaptation (IPCC 2022a), adjusting the discount rate along the lines of Azar and Sterner (1996) substantially increases the level of abatement that is warranted by a CBA of climate change.

Others, such as Arrow et al. (2013, 2014), have argued for discount rates that start relatively high but decline over time. Weitzman (1998), for example, has argued that there is fundamental uncertainty about the long-term future, which means we do not know what interest rate will then apply. It also means that only a state of the long-term future with low discount rates has any relevance for today, as all other states of the world have become irrelevant due to the power of compound discounting at a high rate. Hence, while we can apply a high discount rate for the immediate future, the rate should decline for values in the long-term future. Weitzman's (1998) proposition, buttressed by Gollier and Weitzman (2010), has sparked new interest in the issue of so-called hyperbolic discounting or discounting at a declining rate (see, for example, Portney and Weyant 1999). Discount rates that decline over time will also result in more emission reductions than would be deemed optimal with conventional discounting. Heal (2009, p. 8), however, points out the weakness of a declining discount rate, namely, its time-inconsistency: 'Any intertemporal plan constructed using such a discount rate will be dynamically inconsistent, in the sense that if we follow it for a period of time and then stop and ask what is the best continuation from where we are, it will not be the plan that we originally adopted'.

The Stern Review (Stern 2007) is not the first, but certainly the most prominent study to have shown that applying a low discount rate favours much more drastic and immediate action compared to Nordhaus's analysis. There are of course many aspects that distinguish the Stern Review from previous studies. Some of them are based on laudable innovations, such as the more comprehensive treatment of future uncertainty and its acknowledgement that the expected growth rates of consumption, and therefore one part of the discount rate, are endogenous to future paths of emissions and damage from climate change. It is impossible to do justice to the detail, breadth, and depth of a report of almost 700 pages here. Instead, I will concentrate on the issue of the discount rate, which has an overwhelming impact on the economics of climate change. Contrary to Nordhaus, who follows the descriptive approach, Stern (2007) endorses the prescriptive approach and sets the pure rate of time preference, ρ, essentially to zero. He also assumes a value of one for $\eta(C)$, which implies logarithmic utility in the social welfare function and, thus, some mild aversion to income inequality. Concretely, it is assumed that equal proportional (that is, percentage) increases in consumption are of equal social value independently of the consumption level of the individual or generation. In plain terms, if the current generation has consumption level of 10 and some future generation has consumption level of 20, then one extra unit of consumption for the poorer current generation (equivalent to 10 per cent extra consumption for the present) is counted equal to two extra units of consumption for the future generation that is twice as rich (also equivalent to 10 per cent extra consumption for the future). A pure rate of time preference of essentially zero, added to the forecasts of future consumption growth made by Stern (2007) multiplied by an elasticity of marginal utility of consumption of 1, together generate an overall discount rate of something like 1.4 per cent in the Review, but variable depending on emission and climate change paths.

Critics of the Review have been quick to highlight the crucial role of the discount rate (Mendelsohn 2006; Tol and Yohe 2006; Dasgupta 2007; Nordhaus 2007, 2008, 2011a). Some argue that low discount rates, like those employed in the Review, are simply inconsistent with the allocation of income towards consumption and savings by the current generation. Specifically, if the current generation were serious about employing such a low discount rate, it would have to consume far less now and invest the enhanced savings for the benefit of the future. That it does not do so is taken as evidence by critics that the current generation does not embrace such low discount rates, and that therefore higher discount rates should be employed.

Although I have some sympathy for the arguments in favour of a low discount rate, ultimately, I think they are not persuasive as long as one does not simultaneously abandon the substitutability assumption. While it is true that future generations are not present in today's markets, the actual rate of discount used by the present generation does not violate the WS constraint *if* consumption is rising over time. If future generations were around and could reveal their preferences in today's markets, investment in man-made and human capital would be higher, the real rate of return on capital and hence the discount rate would be lower, and consumption would rise *still faster* over time. But if the substitutability assumption is valid, then there is no compelling justification to lower the rate of discount for reasons of sustainability if non-declining utility can already be ensured by the higher rate of discount that mirrors existing real rates of return on capital. Furthermore, low discount rates are contestable on ethical grounds as well. This becomes clear by looking at worst-case scenarios. Assume that the world fails to follow the Stern Review's recommendations and that it will achieve only very modest emission reductions over the next decades. In this case, the Review predicts a substantial loss of output (consumption) for far-off future generations, possibly up to 20 per cent or even up to 35.2 per cent. However, because of baseline consumption growth, the future will still be much better off than the present, despite climate change damage. For example, based on the assumptions in the Review, even in the worst-case scenario, the future generation of the year 2200 will still be eight times better off than the present one (rather than 12.3 times better off without climate change). Within the CBA framework of the Review, allowing such damage to occur is clearly suboptimal and inefficient. But the worst that can happen if the world fails to heed the Review's advice and employs a higher discount rate is that the distant future is only much, much better off than the present instead of being much, much, much better off. That is too bad, but it is not really a tragedy.

If future generations are far better off than the present anyway, then there is no compelling reason for employing a low discount rate on the grounds of inter-generational fairness. As Lind (1995, p. 384) put it back in 1995:

> Can we justify current generations sacrificing 2–3 per cent of GWP [gross world product] to increase the wealth of future generations who even after deduction for the high damage scenario are 2–15 times richer than the present generation? The answer is clearly no on the basis of intergenerational equity, which must weigh in favour of the current generation.

Again, clearly, such reasoning depends on the validity of the substitutability assumption.

What about the argument of Azar and Sterner (1996)? Here things are somewhat different. If we discount future values because they accrue to richer people in the future, then it is consistent to count values that accrue to the future *intra*-generational poor differently from those that accrue to the rich. With climate change, there will be winners and losers, and it could be argued that the future beneficiaries of emission abatement are located mainly in some of the future developing countries, whereas those who are likely to undertake the abatement investments are located mostly in the present developed countries. Furthermore, it could be argued that due to this difference in location, the future beneficiaries will not be better off (very much) than the current people asked to undertake sacrifices: even if the now poor will be much better off in 100 years, they need not be much better off, if at all, than the currently rich. Hence, it would follow that, given a zero pure rate of time preference, the discount rate should be equal to 0 per cent or only slightly above. It might even be negative!

Azar and Sterner's (1996) reasoning is consistent with the spirit of the Ramsey formula. But their reasoning is inconsistent with the actual provision of aid from the current rich to the current poor, which is of a rather limited magnitude.[16] As Schelling (1995, p. 397) put it:

> It would be strange to forgo a per cent or two of GNP for 50 years for the benefit of Indians, Chinese, Indonesians and others who will be living 50 to 100 years from now – and probably much better off than today's Indians, Chinese, and Indonesians – and not a tenth of that amount to increase the consumption of contemporary Indians, Chinese, and Indonesians.

But such a policy would also be hugely inefficient, even if the current rich were ready to make large sacrifices for the sake of people living in developing countries either now or in the future. Given the validity of the substitutability assumption, there are many more attractive investment options from the viewpoint of the beneficiaries than investing in emission abatement. As Nordhaus (1991b, p. 57) notes, real rates of return to investment in education are extraordinarily high in poor countries, which he reports to be about 26 per cent for primary education, 16 per cent for secondary education, and 13 per cent for higher education. No doubt, poor people would be much better off if scarce resources were invested in these opportunities rather than in combating climate change. Given substitutability, Schelling (1995, p. 401) is right in expecting that 'if offered a choice of immediate development assistance or equivalent investments in carbon abatement, potential aid recipients would elect for the immediate' – as would their future descendants if they had a voice.

Equally important, it is unclear whether any equity weighting does in fact result in more stringent abatement policies regarded as optimal. Nordhaus introduces equity weighting in his model runs, and he finds that doing so tends to reduce the social cost of carbon and thereby optimal emission reductions. The intuition behind this seemingly surprising result is straightforward: 'The result is a reflection of the (modelling) fact that the beneficiaries of reduced damages are richer than today's generation, who make the investments in slowing climate change' (2011a, p. 16).

2.4.3 Critique of the Nordhaus Approach (II): Extreme Outcomes

A second critique of the Nordhaus approach centres around what Weitzman (2011, p. 276) calls 'deep structural uncertainty about climate extremes': the low-probability but extreme outcome consequences of climate catastrophes. In a series of papers, Martin Weitzman (2009a, 2009b, 2009c, 2010, 2011, 2012, 2014; Wagner and Weitzman 2018) has developed this critique of conventional cost-benefit analyses of climate change, of which Nordhaus's studies are the most important ones.[17] If the probability of extreme damages from climate catastrophes resulting in extreme losses to consumption does not diminish sufficiently rapidly, then we are confronted with what is called 'fat tails' in the distribution of climate change damages. Put simply, there is a small likelihood that even relatively modest further increases in the carbon concentration in the atmosphere to, say, 500 to 600 parts per million of CO_2 equivalent lead to very large temperature increases (say, beyond 6ºC or even 8ºC). There is then a small likelihood that these very large temperature increases lead to much more extreme and utterly catastrophic damages than expected. This, combined with uncertainty about the right discount rate to use (see the discussion above), would call for stringent emission abatement in order to insure against such potential truly catastrophic outcomes. This second critique of the Nordhaus approach is not entirely disconnected from the debate over the right discount rate to use. As Dietz (2011) shows, even catastrophic outcomes sufficiently far in the future become sufficiently small in present value terms and therefore matter very little if the discount rate is sufficiently high.

Nordhaus (2011b, 2012), in turn, has dismissed this case for stringent emission abatement as largely speculative and insufficiently founded in currently available science. He argues that Weitzman overestimates the likelihood of extreme temperatures and catastrophic climate damages. He concludes that 'a loaded gun of strong tail dominance has not been discovered to date' (Nordhaus 2012, p. 199). Consistent with this general point of view, which is rather dismissive of the non-negligible risk of truly catastrophic outcomes, in Nordhaus (2019b, p. 12261) he suggests that even the risk of the complete disintegration of the Greenland ice sheet makes only 'a small contribution to the optimal stringency of current policy or to the overall social cost of climate change'.

Nordhaus (2012, p. 217) points out that there are other dangers to humankind that could exhibit 'fat tail' damage distribution properties, 'from exotic events such as asteroids and robotic enslavement to more mundane events such as tsunamis, nuclear meltdowns, and financial collapses'. To these, Pindyck (2010, p. 13) adds biological terrorist attacks or a highly contagious as well as highly lethal 'mega-virus' that spreads uncontrollably. If all these potential catastrophes prompted us to spend large sums of money to insure against them, this would diminish our willingness (and possibly even our ability) to spend sufficient money on insuring against any single one of them.

2.4.4 Critique of the Nordhaus Approach (III): Substitutability of Natural Capital

The discussions about the 'correct' discount rate to use and the possibility of truly catastrophic climate change damages are important ones, but they fail to deal with what I regard as the weakest point of Nordhaus's approach, namely, the assumption of substitutability of natural capital. Given this assumption, large-scale emission abatement is *either* ethically dubious because future generations are better off than the present generation anyway and inconsistent with the observed magnitude of current savings required to justify very low discount rates, *or* it is inconsistent with the behaviour of the currently rich towards the currently poor and imposes upon the poor inefficient investments whose financial resources they would rather use for different purposes if given a choice.

One way or another, some critics of Nordhaus have therefore made arguments that point in the direction of limited substitutability or even non-substitutability of natural capital (Rabl 1996; Neumayer 1999a, 2007; Philibert 1999; Spash 2002; Gardiner 2004; Page 2006; Helm 2008; Sterner and Persson 2008; Weitzman 2009b, 2009c, 2010). While the Stern Review (2007) does not explicitly make such an argument or formally model limited substitutability in its quantitative analysis, many of the arguments put forward in the Review in its wider qualitative analysis can in fact be seen as making such a case. On this, see also Dietz et al. (2007).

The suggestion to treat environmental costs and benefits differently from other values is not a new one. In a seminal contribution from the 1970s, Krutilla and Fisher (1975) put forward an argument that became known as the Krutilla–Fisher approach. They presume that environmental benefits are likely to increase *relative* to other benefits in the economy – for example, because future richer people will appreciate relatively more environmental amenities if the income elasticity of demand for environmental amenities is bigger than 1 (that is, if environmental amenities are luxury goods). De facto, this increase in relative value means that environmental benefits are discounted at less than other values or maybe even not at all. If the relative importance of environmental benefits grew sufficiently strong, they could even count more than their nominal value so that, de facto, they would be 'discounted' at a negative rate. Krutilla and Fisher also presume that some of the benefits from environmental destruction are likely to depreciate over time. The developmental benefits from dam construction, for example, are likely to depreciate over time as superior technologies become available. De facto, this depreciation in relative value means that these benefits are discounted more heavily than other, especially environmental, values. Note the words *de facto*: formally, the same uniform discount rate is applied to all values; it is rather the values that appreciate or depreciate, respectively, before they are uniformly discounted to present values. Philibert (1999), on the other hand, also stresses that the value of non-reproducible environmental assets should be assumed to increase in the future but calls for discount rates that slowly decrease over time.

Rabl (1996) has applied the Krutilla–Fisher rationale to climate change under the presumption that the environmental benefits of combating climate change are likely to rise over time. Similarly, but without recourse to the Krutilla–Fisher approach, Tol (1994) examines the effect of letting intangible goods, whose values increase over time with per capita income, enter the utility function. Not surprisingly, Rabl and Tol find that higher emission abatement is warranted than Nordhaus did. Sterner and Persson (2008) use Nordhaus's model with modifications, showing that under the assumption that the supply of environmental services is negatively affected by climate change and that environmental services enter a utility function with a constant relative risk aversion, then much more aggressive emission reductions will follow from Nordhaus's model, despite using the same discount rate as Nordhaus does.

The Krutilla–Fisher approach and related arguments go some way in departing from the substitutability paradigm. What it says is that natural capital becomes more difficult to substitute over time as its relative value increases.

At the same time, the approach still assumes some form of substitutability. Not surprisingly, proponents of SS, with their belief in the non-substitutability of natural capital, go all the way and represent the opposite extreme to Nordhaus's computations. Their argument is that climate change threatens to impose non-substitutable damage to and loss of natural capital. While not every effect of climate change will be detrimental to natural capital, a consensus is emerging (see IPCC 2021) that it will lead to or at least can lead to:

- a drastic increase in ecosystem degradation and a corresponding loss of biodiversity;
- rising sea levels and an increase in the frequency and intensity of storm surges, together resulting in increased coastal flooding and erosion;
- a change in the species composition of forests, with the possible loss of species and the disappearance of entire forestry types;
- an increase in the frequency and range of pests, pathogens, and fires and the further spread of invasive species displacing native flora and fauna;
- an increase in desertification and droughts;
- a disruption in mountain resources of food and fuel for indigenous people;
- an increase in stress on freshwater resources due to melting glaciers and altered rainfall patterns;
- an increase in the salinity of estuaries and freshwater aquifers;
- a disruption of saltwater marshes, mangrove ecosystems, coastal wetlands, coral reefs, coral atolls, and river deltas due to, among others, increased coastal flooding;
- an increased occurrence of heat waves and floods coupled with an increase in their intensity, with damaging effects on ecosystems, including soil erosion, and human health;
- an increase in the potential transmission of infectious diseases like malaria and yellow fever.

In putting ecosystems under severe stress, climate change can therefore damage the capacity of natural capital:

- to provide freshwater, food, fibre, medicines, and energy;
- to process and store carbon and other nutrients;
- to assimilate waste, purify water, and regulate water runoff;
- to control floods, soil degradation, and beach erosion;
- to provide opportunities for recreation and tourism.

Given this list of potentially severe damages to natural capital due to climate change, it should come as no surprise that SS calls for aggressive policies to combat climate change since natural capital as such should be kept intact. While some warming might be unavoidable, SS would try to ensure that the future is harmed as little as possible, even if it is materially better off than the present. According to this view, climate change will degrade natural capital, and since natural capital cannot be substituted for, climate change must be contained as much as possible regardless of the costs of doing so (Spash 2002). This position is shared by many environmentalists and stands in marked contrast to Schelling's (1991, p. 221) belief that 'any disaster to developing countries from climate change will be essentially a disaster to their economic development'.

The proponents of SS regard the disturbance of the global atmospheric cycle as a harm to future generations that cannot be compensated for by higher consumption, even if future generations are materially much better off. Their argument is that climate change, at least when above a certain threshold, damages the utility of future generations to such an extent that they are worse off than the present generation, regardless of the baseline growth in material consumption. This may sound implausible to many neoclassical economists, but only because they often overestimate the extent to which consumption growth leads to actual utility gains (see Easterlin 2003). Once it is acknowledged that further consumption growth may only lead to a small rise in utility, then the proposition that climate change may actually decrease utility despite consumption growth is not too far-fetched. Of course, such an argument must ultimately rest on a normative judgement. This is for two reasons. First, there is no way of knowing future generations' preferences. Second, there is similarly no way of adequately valuing the utility loss from, say, the loss of glaciers, wetlands, forests, and coral reefs, the damages to coastal, marine, arctic, mountain, and other ecosystems, and the likely massive rise in the rate of species extinction, which are all likely to be associated with already moderate temperature increases.

In consequence, SS calls for limiting climate change, which should be set as an explicit policy objective. That lowering the discount rate would coincidentally achieve the same result on this aspect should not distract from the main message, namely, climate change threatens to inflict irreversible and non-substitutable damage to and loss of natural capital. In some sense, Nordhaus himself is much clearer about this than some of his critics. His recommendation to those who want to limit climate change because of perceived limits to the substitutability of natural capital is that they should not mess around with the discount rate to achieve the desired outcome but should argue for the desired outcome explicitly and directly. This becomes clear from the following quotation (Nordhaus 1999, p. 145):

> The best approach will generally be to identify the long-term objective and to directly override market decisions or conventional benefit–cost tests to achieve the ultimate goals. Focusing on ultimate objectives shows trade-offs explicitly, makes the cost of violating benefit–cost rules transparent, and allows public decisionmakers to weigh options explicitly rather than allowing technicians to hide the choices in abstruse arguments.

2.4.5 The Real Controversy

Whether and how to act against climate change cannot be decided on the basis of 'hard numbers' because there are no 'hard numbers' when it comes to climate change. To outsiders, the CBA studies of economists may suggest otherwise. But those who understand what the studies do also know two things. First, many effects of climate change simply cannot be adequately monetarily valued. Second, what can be valued needs to be transformed from values in the far distant future to present values, and any CBA recommendation is therefore crucially dependent on the discount rate used, which is in turn inextricably linked to normative value judgements.

Of course, the issue of the right discount rate is somewhat more complex than I have portrayed it in Section 2.4.2, p. 35 – I refer readers to, for example, Yang (2003); Tol (2005); Weikard and Zhu (2005); Dasgupta (2007); Quiggin (2008) and Stern (2008, 2014a, 2014b, 2015). I wish to emphasise, however, that there is no 'right' discount rate, particularly not for such long time spans as those relevant to climate change (that is, several centuries). The choice of the pure rate of time preference as well as the elasticity of marginal utility of consumption[18] necessarily derive from ethical value judgements that, because they are normative judgements, can and will always be contested.[19] One way or the other, decision-making towards climate change is heavily influenced by ethical choices. But it is important to face the real issues when making ethical choices and to orient the discussion towards what matters to people.

I contend that those who believe the current generation should take immediate and decisive action against climate change need to go beyond arguing for a low discount rate and make the case for limited or even zero substitutability of certain forms of natural capital impacted by climate change. Alternatively, they need to argue that there is a sufficiently strong case to spend large sums of money on insuring against the possibility of catastrophic consumption losses (rather than other potentially catastrophic dangers to humankind), independently of the issue of substitutability of natural capital. Of course, the two lines of argumentation can, in principle, be combined with each other. In fact, the case for stringent emission control is strongest if certain forms of natural capital affected by climate change have limited or no substitutability, and if the money spent on emission control turns out to be a wise insurance policy against potentially catastrophic consumption losses.

The upshot is that resting one's case on a low discount rate alone is utterly unconvincing. This is because the case for action crucially depends on asking the current generation to make substantial sacrifices to cushion consumption losses for future generations that are much better off than the present generation anyway. This will not be very popular once voters understand what they are being asked to do, namely, to face economic costs in order to aggressively reduce greenhouse gas emissions.

I also contend that the non-substitutability issue is much closer to the real concerns of people. By contrast, CBA studies of climate change and the debate on the discount rate are strangely out of touch with reality. Voters and politicians who favour decisive and urgent action surely do not do so because they want to save much better-off future generations from some consumption loss that, even if it happened, would still leave them much better off than the present generation (see Sterner and Persson [2008] and Stern [2022] for a similar view). Instead, they are concerned that climate change is like no other and that its sheer scale and extent of damage threatens to create a new bio-physical world that either leaves the future worse off or violates their inalienable rights to enjoy natural capital, despite consumption growth. Article 2 of the United Nations Framework Convention on Climate Change calls for 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. It does not call for maximising the present discounted value of an inter-temporal social welfare function built on questionable assumptions about the substitutability of natural capital. Nicholas Stern, who should be regarded as the main counterpart from within the economics profession to the approach taken by William Nordhaus, is spot on when he argues as follows (Stern 2022, pp. 1262ff.): 'In my view, the risks, including the possibility of the loss of life of billions, extended and severe conflict, destroyed biodiversity, and profound loss of quality of life, livelihoods and well-being, are not well captured in narrow utility-based approaches. Neither the standard objective functions in economics, nor indeed the underlying models, capture the challenges at issue'.

2.5 CONCLUSION

This chapter has laid the foundations for the analysis of the coming chapters. In Section 2.1, SD was defined as development that does not decrease the capacity to provide non-declining per capita utility for infinity. Notably, SD was not defined in direct utility terms, but in terms of the capacity to provide utility. The relevant terms were explained, and the economic paradigm was chosen as methodology because both WS and SS are essentially economic. In

Section 2.1, it was merely assumed that the current generation is committed to SD, but in Section 2.2.1, some reasons based on Kant's deontological moral theory and Rawls's 'Theory of Justice' were provided for why such a commitment might be a reasonable choice. The commitment might suffer from a time-inconsistency problem, however, as argued in Section 2.2.2. No definite solution to this problem could be provided, but the argument was put forward that if each generation tries to persuade the next generation that a commitment to sustainability is a 'just' thing to do, then there might be a chain of commitment such that the time-inconsistency problem can be mitigated, if not fully overcome.

In Section 2.2.3, two popular misunderstandings about SD were resolved. It was shown that SD does not lock society into eternal poverty if it is poor at the start of its commitment to sustainability because SD does not require constant utility throughout time. Hence, sacrifices for the sake of future generations are anything but ruled out. It was also shown that SD does not demand the choice of greatly inferior utility paths if a temporary decline in utility along the path can be avoided via increased saving before the expected decline. Section 2.2.3 is important for the later analysis because if these claims about SD were correct, a commitment to sustainability could hardly be seen as a defensible choice for society to make. Section 2.3 presented the two paradigms of sustainability. The essence of WS is its assumption that natural capital is substitutable. In contrast, the essence of SS is that it regards natural capital as non-substitutable. To highlight the importance of these differing assumptions, Section 2.4 looked at the case of climate change. It was shown that whether natural capital is regarded as substitutable, as in the WS paradigm, or non-substitutable, as in the SS paradigm, has major consequences for decision-making on climate change. If natural capital is substitutable, then there is little compelling justification to very aggressively reduce carbon dioxide and other greenhouse gas emissions, unless a strong case can be made that such emission reductions are necessary in order to insure against the possibility of catastrophic consumption losses. If, on the other hand, natural capital is non-substitutable, then the massive damage to and irreversible loss of natural capital inflicted by climate change justifies drastic and immediate action. The proper conflict between those who demand an aggressive abatement policy and those who call for only minor abatement efforts should therefore mainly be about the substitutability of natural capital, not about the 'correct' rate of discount. The next chapter takes a closer look at the validity of these opposing assumptions with respect to the substitutability of natural capital.

NOTES

1. Except for jewellery, perhaps, and, even there, it could be said that gold, silver, diamonds, and so on are used to produce the consumption good jewellery and are therefore not directly contributing to utility.
2. Note, however, that the so-called Brundtland Report (World Commission on the Environment and Development 1987), which was quite influential in promoting the debate on sustainability, put emphasis on both inter- and intra-generational justice. From this report stems also the best-known non-academic definition of SD as development that 'satisfies the needs of the present without compromising the needs of the future' (chapter 2, paragraph 1). Also, in 'Southern' debates about SD, the notion of intra-generational fairness features prominently (for example, Guha 1989; Agarwal and Narain 1991; Teng et al. 2016).
3. In other writings, I have put priority on questions of intra-generational fairness. See, for example, Neumayer (2000a).
4. A (pure) public good is characterised by two characteristics: first, non-rivalness in consumption and second, non-excludability. The former means that the consumption of a public good by any individual does not diminish the consumption possibilities for any other individual. The second characteristic is more problematic. It means that nobody can be excluded from consuming the good. While this might sound rather innocuous, it has the negative consequence that in general there is no sufficient incentive for any private individual to produce the good. This is because, since nobody can be excluded from consumption, nobody can be made to pay for the costs of providing the good either. But if the costs cannot be recovered, the good will not be privately produced in the first instance. This is the reason why public goods are usually referred to as prime examples of the necessity of government intervention.
5. Rawls (1972, p. 140) himself claims that the notion of the veil of ignorance is already implicit in Kant's moral philosophy.
6. Rawls actually spoke of many individuals, but given his information assumptions, the number of individuals can be reduced to one representative individual without loss of generality.
7. Anand and Sen (2000) provide a complementary justification for sustainability under the notion of 'usufruct rights', where each generation has the right to enjoy the fruits of accumulated capital without depleting it.
8. Note, however, that Rawls (1972, pp. 284ff.) did not apply his principle to inter-generational matters.
9. This holds true as long as there is no *exogenous* technical progress, that is, technical progress that is independent of the accumulation of man-made capital, which is the underlying assumption in Solow (1974a).
10. This is an important point to note. Statements such as 'sustainability is a very tough objective for industrial societies to meet' (Jacobs 1997a, p. 371) are contingent on a different definition of sustainability to WS.

11. Of course, much depends on the exact model specifications. But there are present-value maximisation models (for example, Dasgupta and Heal 1974; Solow 1974a) with either sub-exponential or zero technical progress that result in eventual catastrophe for *any* positive constant discount rate (Pezzey 1995, p. 11).
12. Throughout the book, I concentrate mostly on CO_2 emissions since it is the major greenhouse gas. The reader should always keep in mind, however, that an efficient strategy to combat climate change would have to take into account all greenhouse-relevant emissions.
13. https://www.nobelprize.org/prizes/economic-sciences/2018/nordhaus/facts/
14. https://unfccc.int/process-and-meetings/the-paris-agreement
15. https://www.bbc.co.uk/news/science-environment-68110310
16. I guess that Azar and Sterner (1996) would demand raising this level of aid so as to maximise world social welfare, if only to remain consistent with their own approach.
17. A related argument is put forward by Millner et al. (2010). They argue that our knowledge of climate change impacts may be of such low quality that the axioms of expected utility theory break down and, instead, an axiomatic framework that takes into account 'ambiguous beliefs' needs to be adopted. They show that under certain conditions, adopting such a framework also warrants stringent emission abatement policies.
18. This elasticity need not be constant but could be a function of future expected consumption growth. I, for one, do not think that giving up 1 per cent of consumption today for the purpose of giving 1 per cent extra consumption to much better-off future generations is ethically desirable.
19. Note that this is not equivalent to uncertainty about the discount rate and therefore not subject to Weitzman's (1998) argument for declining discount rates in the long run. His argument applies to uncertainty about the growth rate of future consumption, but not to the choice of the pure rate of time preference or the elasticity of marginal utility of consumption. Economists and other social scientists are not uncertain about these, but simply differ in their choice because of differing value judgements.

3. Resources, the environment, and economic growth: is natural capital substitutable?

This chapter discusses a question that arises from the discussion of the two paradigms of sustainability in the previous chapter: if they have such starkly differing assumptions about the substitutability of natural capital, how can we know which paradigm is 'correct'? I will argue that both paradigms ultimately rest on non-falsifiable beliefs about the future. There can, therefore, be no clear answer on whether natural capital is substitutable or not.

Section 3.1 puts the discussion into context by providing a brief history of resource and environmental concerns. Section 3.2 looks at natural capital as an input into the production of consumption goods and services, including agricultural food production. It suggests that the resource optimism of WS can be expressed in four propositions and critically assesses each one of them. It looks at:

- Substitution of a resource with other resources.
- The role of prices in overcoming resource constraints.
- Substitution of natural resources with man-made capital.
- The role of technical progress in overcoming resource constraints.

Section 3.2, in essence, argues that the substitutability assumption of WS is more plausible than the non-substitutability assumption of SS when it comes to the 'source' side of the economy.

Then, Section 3.3 turns to environmental degradation. Section 3.3.1 looks at the substitutability of natural capital as a direct provider of utility and examines whether future generations can be compensated for long-term environmental degradation with increased consumption opportunities. Section 3.3.2 analyses the environmental consequences of economic growth. It presents the theoretical case for environmental optimism, which holds that economic growth is good for the environment, at least in the long run, and the theoretical case for environmental pessimism, which holds that economic growth is bad for the environment. Since theory is shown to be unable to resolve the dispute, the empirical evidence is assessed.

Section 3.3 essentially argues that the non-substitutability assumption of SS is more plausible than the substitutability assumption of WS when it comes to environmental amenities provided by natural capital and as concerns the pollution absorptive capacity of the environment. More plausible does not mean 'correct', though, and Section 3.4 concludes that both paradigms are non-falsifiable in the end.

3.1 A SHORT HISTORY OF RESOURCE AND ENVIRONMENTAL CONCERN

Modern concern that the limited availability of natural resources will constrain the possibilities for consumption growth, or for that matter, even non-declining consumption, dates back to at least Malthus (1798). He was convinced that the limited availability of land put an absolute scarcity constraint on food consumption growth. While population rises at a geometric (exponential) rate, the production of food could only be expanded at an arithmetic (linear) rate, Malthus thought. Hence, he believed that the population could grow only until the minimum subsistence level of per capita food consumption was transgressed and had to decline sharply afterwards – only to grow and hit the absolute scarcity constraint again in an apparently endless vicious circle. Later, Jevons (1865) warned against a running out of coal as an energy resource and expressed concern about the detrimental consequences of rising coal extraction costs on economic growth and the competitiveness of British industry.

We know by now, of course, that both had been wrong: population grew tremendously in the 19th century and afterwards, and, in 2020, worldwide proven reserves of coal would last for another 139 years at current production rates (Energy Institute 2024). Moreover, coal is not seen as an essential resource anymore. Malthus and Jevons committed mistakes that other resource pessimists repeated later. Malthus did not consider the power of technical progress, and he was not aware of the fact that, as Ricardo (1817) first realised, land availability is more a question of relative, as opposed to absolute, scarcity; that is, land is a heterogeneous resource and it is possible to get the same amount of nutrition out of a lower-quality acre by investing more inputs. Jevons, for his part, underestimated the scope for exploration and finding new reserves of coal and neglected the powerful possibilities of substituting other energy resources for coal. One has to keep in mind, however, that concern about the availability of natural resources was deeply rooted in mainstream economic thinking of that time and many classical economists, most notably Mill (1862) and Ricardo (1817), shared the belief that the economy had to stop growing sooner or later due to a resource constraint.[1] In those days, economics had a reputation as a 'dismal' science (Barnett and Morse 1963, p. 2).

It was not before the so-called marginal revolution and the rise of neoclassical economics at the turn of the century, mainly due to Alfred Marshall, Léon Walras, and Irving Fisher, that concern about resource availability vanished. In its leading macroeconomic metaphor, the income–expenditure cycle, the depletion of natural resources is non-existent in a seemingly endless circular exchange of value in which households provide labour for producing goods and services for which they receive income, which is in turn exchanged for the produced goods and services. Reality seemed to buttress this new thinking: the economy kept on growing, especially in the 'golden years' after the Second World War, and even if it did not, as in the Great Depression, the reasons were no longer sought in limited natural resources. This is not to say that there were no pessimistic outlooks. The US President's Materials Policy Commission (1952a, p. 1), for example, saw 'many causes for concern' in its examination 'of the adequacy of materials … to meet the needs of the free world in the years ahead' for the struggle against the 'threats of force and of a new Dark Age which rise from the Communist nations'. Overall, however, resource optimistic perspectives prevailed.

Concern about natural resource availability emerged again with the publication of the Club of Rome's 'Limits to Growth' report (Meadows et al. 1972). This concern became popular and widespread after the quadrupling of world oil prices, as OPEC first boycotted the US and the Netherlands and later other developed countries as well for their support of Israel in the Yom Kippur War in 1973 and soon learned to exercise leverage over the OECD countries.[2] Meadows et al. prophesied that the exhaustion of essential mineral and energy resources would make economic growth infeasible at some point in the 21st century. Therefore, a halt to economic growth and even an eventual economic contraction might be enforced through resource scarcity. Essentially the same message was echoed by the Global 2000 Report to the President of the US in 1980 (Barney 1980) and 20 years after their first report, Meadows et al. published an updated but hardly revised restatement of their argument (Meadows et al. 1992).

Economists, contrary to the wider public, this time did not share the concern about resource availability. Only some 'outsiders', often regarded as eccentrics by the mainstream economics community, had sympathy with the report's motivation and goal, without overlooking the criticisms that could be raised against it (Georgescu-Roegen 1971, 1975; Mishan 1974; Daly 1977 [1992a]). In economic terms, Meadows et al. were naive in extrapolating past trends without considering how technical progress and a change in relative prices can work to overcome apparent scarcity limits. This criticism was put forward vigorously in a fierce attack by neoclassical economists and other scientists who rejected the report(s) as pure nonsense (Beckerman 1972, 1974; Cole et al. 1973; Nordhaus 1973, 1992; Solow 1974b). For them the depletion of non-renewable resources had to be tackled with traditional economic instruments and had to be taken on board by neoclassical economics (Dasgupta and Heal 1974; Solow 1974a, 1974c; Stiglitz 1974) – but limits to growth due to resource constraints were not considered a problem.

For a long time, environmental problems were regarded as temporary rather than enduring and were thus by most people not perceived as a fundamental problem of industrialisation and economic growth per se. The public awakened to the detrimental side effects of industrialisation and rapid economic growth in the early 1960s, when Carson (1962) expressed her fear about a 'silent spring' due to the death of birds being exposed to DDT. The book became very popular and so, albeit slowly, did the environmental movement (for an overview, see McCormick 1989). It was not before ozone layer depletion, climate change, and biodiversity loss became major issues in the 1980s, however, that environmental degradation was perceived as a potential constraint to economic growth as such. Interest by that time shifted away from natural resource availability towards the environment as a medium for assimilating wastes (from 'source' to 'sink') (Pearce 1993b).

Indicative of this trend is that the second and third 'Club of Rome' reports by Meadows et al. (1992, 2004) were much more concerned with environmental degradation than the first report (Meadows et al. 1972). Nevertheless, environmental pessimists believe that economic growth in the long run is constrained both by resource availability and by its detrimental effects on the environment. Again, mainstream economists, although expressing some concern about environmental pollution, do not believe in environmental limits to growth (Ravaioli 1995; Illge and Schwarze 2009).

The following section starts with the 'source' side of the economy in analysing the availability of resources for the production of consumption goods. So far, the pessimists have been wrong in their predictions. But one thing is also clear: to conclude that there is no reason whatsoever to worry on the basis that the pessimists have been wrong in the past is tantamount to committing the same mistake the pessimists are often guilty of – that is, the mistake of extrapolating past trends. The future is inherently uncertain, and it is humans' curse (or blessing, if you like) not to know with certainty what the future will bring. The past can be a bad guide to the future when circumstances are changing. The fact that the alarmists have regularly and mistakenly cried 'wolf!' does not imply that the woods are safe.

3.2 RESOURCE AVAILABILITY

First, let us have a look at natural capital as an input in the production of consumption goods and services. Just how scarce are natural resources and can they easily be substituted for by man-made capital or technical progress?[3] The resource optimism of WS can be summarised in four propositions (see the Box 3.1).

If resource optimism is correct, then there is no need to worry about the depletion of natural resources: either the world will not run out of a resource or it will not matter if it does, since another resource or man-made capital will function as a substitute.

BOX 3.1 A SUMMARY OF RESOURCE OPTIMISM IN FOUR PROPOSITIONS

Resource optimism holds that if some resource A is becoming scarce in an economic sense,[4] its price will rise, which triggers the following four mutually non-exclusive effects:

a) Demand shifts away from resource A and another resource B becomes economical and replaces resource A.
b) It becomes economical to explore and extract as well as recycle more of resource A. As a consequence, the price of resource A will decline again, thus signalling an ease in economic scarcity.
c) Man-made capital will substitute for resource A.
d) More effort is put into technical and scientific progress in order to reduce the necessary resource input per unit of output, thus easing any resource constraint. Additionally, technical and scientific progress make resource extraction cheaper, thereby making the extraction of a resource's lower-quality ores economical, or resource deposits that were hitherto not profitably extractable now become economical to extract. As a consequence, prices will decline again, signalling an ease in economic scarcity.

3.2.1 Substitution with Other Resources

Let us first look at proposition (a) of resource optimism, which essentially says that a resource B will substitute for resource A if the latter becomes scarcer. If the proposition is correct, then there is no need to worry about the depletion of resource A and, since A could be any resource, there is no need to worry about the depletion of any resource at all. The point is that the depletion of a resource does not matter economically if it is or becomes unnecessary for production. This was what Beckerman (1972, p. 337) had in mind when he commented rather sarcastically on the first 'Limits to Growth' report from the Club of Rome:

> Why should it matter all that much whether we do run out of some raw materials? After all … economic growth has managed to keep going up to now without any supplies at all of Beckermonium, a product named after my grandfather who failed to discover it in the nineteenth century.

Conversely, the existence of a resource does not matter economically as long as it is without an economic use. As Ray (1984, p. 75) observes:

> All materials used by industry were 'new' at some point in history; they have become 'resources' as a result of scientific and technological advance discovering them and developing their use. Bauxite did not even have a name before it was discovered that it could be processed into a new metal: aluminium.

It is clear that proposition (a) taken to its logical limit, only applies to resources B that are quasi-undepletable. Good examples are solar energy and nuclear fusion. These two examples make clear that ultimately resource B must be something close to what economists call a 'backstop technology'. A backstop technology is a resource that can provide services at constant marginal costs in quasi-infinite amounts (Dasgupta and Heal 1974). If such a resource exists, then the economy can be saved from doomsday for an indefinite time (Prell 1996).

Does proposition (a) contradict or violate the laws of thermodynamics? Not necessarily. The first law of thermodynamics (conservation of mass) states that energy cannot be created anew, while the second law of thermodynamics states that entropy in a closed system is monotonically increasing over time, that is, useful energy is used up and cannot be used over and over again (Söllner 1997, pp. 181, 183). For all human relevance, the universe is a closed system. But note: it is the universe that is a closed system, not the Earth itself, which is an open system in the sense that it is getting a steady, constant, finite influx of energy from the sun. It is a closed system only in so far as it does not exchange matter with the outside. Georgescu-Roegen's (1975, p. 370) suggestion that every car built today implies 'fewer plowshares for some future generations, and implicitly, fewer future human beings, too' due to the laws of thermodynamics is *not* correct in a system that receives a steady, constant, finite influx of energy, where it is not compelling that entropy permanently increases. Of course, Georgescu-Roegen was not so naive as to overlook the fact that the Earth is not a closed system. He merely claimed that using solar energy needs more non-solar energy input than is gained in energy eventually

(Georgescu-Roegen 1986, p. 23). This may have been true of early solar technologies but is no longer the case.

Now, controlled civil use of nuclear fusion may remain a scientist's dream forever despite very exciting recent scientific breakthroughs in which it was possible, for the first time, to generate more energy than went into starting the process of nuclear fusion (Maynihan and Bortz 2023). Personally, I believe it will come into effect some time towards the middle of this century. In any case, solar energy comes close to a backstop technology for energy resources, at least in principle: the solar energy influx exceeds total world energy demand at about three orders of magnitude (Smil 2003). Hence, solar energy and hydrogen produced from solar energy (Blanchette 2008), complemented by other renewable energy sources such as wind, tidal power, geothermal, biomass, and so on, hold the greatest promise (Ayres 2008; International Energy Agency 2021, 2023).

The costs of renewable resources, particularly solar and wind power, have decreased dramatically over time and either already are, or will soon become, fully competitive with fossil fuel energy resources in the near future. Installation of new renewable energy capacity for electricity production is on a sharply upward trend. *The Economist* magazine reports predictions that solar energy alone will generate more electricity than all the world's nuclear fission power plants by 2026, more than all its wind turbines by 2027, more than all its hydro dams by 2028, more than all its gas-fired power plants by 2030, and more than all its coal-fired power plants by 2032 (The Economist 2024, p. 46). Coupled with still outstanding technical breakthroughs in battery storage capacity (for times when the sun does not shine and the wind does not blow), from the resource optimists' perspective, there are no technical reasons why renewable energy could not take over the lion's share of world energy demand currently supplied by fossil fuels. True, there are some sectors like aviation, shipping, plastics, ammonia, steel, and cement production that cannot be easily electrified and where renewable energy is less easily applied. Green hydrogen, that is, hydrogen produced by plentiful and cheap renewable energy sources, may substitute for fossil fuels.

On the whole, therefore, from the resource optimists' perspective, there is no fundamental reason why the world economy could not predominantly, in fact almost exclusively, be run on renewable energy resources (International Energy Agency 2021, 2023), which would mean that existing non-renewable resources can last for much longer and become far less economically relevant. *The Economist* (2024) magazine goes as far as suggesting that abundant and ultra-cheap solar electricity will soon represent the hallmark of humankind's future. Except we have been here before. Back in 1954, the chairman of the US Atomic Energy Commission, Lewis L. Strauss, proclaimed: 'Our children will enjoy in their homes electrical energy too cheap to meter' (cited in Smil 2017, p. 438). Will it be different this time?

Against such optimism, Huesemann (2003, p. 21) contends that 'it will be extremely difficult to switch to an industrial and economic system based solely on renewable resources'. Smil (2020, p. 14) similarly warns that 'our dependence on fossil fuels is enormous and … most of the humanity needs more energy and this requirement cannot be met by a rapid expansion of renewables'. He points out that fossil fuels' share in the global primary energy consumption has only decreased marginally from 86 per cent in 1997 to about 82 per cent in 2022 (Smil 2023, p. 17). Five years earlier, his assessment was even bleaker (Smil 2017, p. 441): 'techno-optimists see a future of unlimited energy, whether from superefficient PV [photo-voltaic] cells or from nuclear fusion, … . For the foreseeable future (two–four generations, 50–100 years) I see such expansive visions as nothing but fairy tales.'

Smil is not a resource pessimist, as such, which makes his warnings about the hype generated by resource optimists all the more relevant. By contrast, Trainer (1995, 2010, 2017, 2022) represents an outspoken and explicit resource pessimistic view. He believes that the prospects of renewable resources providing sufficient energy at reasonable economic costs are vastly overestimated, neglecting the difficulties of 'conversions, storage and supply' of renewable resources 'for high latitudes' (Trainer 1995, p. 1009). He suggests that if the world must depend on renewable energy resources only, then it 'must be based on materially simple lifestyles, a high level of local economic self-sufficiency, and a steady-state or zero-growth economy' (p. 1025). Decades after this assessment, he still sees little room for optimism (Trainer 2010, 2017, 2022). He doubts that the technical breakthroughs in storage capacity to make full use of renewable energy sources will ever materialise (Trainer 2017) and argues that a renewable energy backstop technology is neither possible nor affordable (Trainer 2022). Relatedly, Moreau et al. (2019) argue that there are insufficient reserves of metals of various types and of other materials to fully switch energy systems to renewable energy by 2050.

Whether the resource optimists' belief in renewable energy backstop technology will come true is therefore unclear. Projections into the future are highly dependent on prophesying the *future* development of scientific and technical progress; the *future* growth of economies, populations and world energy demand; and on predicting *future* changes in energy and environmental policies. Beyond the very immediate time span, these projections *necessarily* become closer and closer to sophisticated guesses and speculations lacking a sound and reliable scientific basis. Mistakes in past projections represent a case in point: many reports in the early 1970s overestimated the amount of nuclear fission power the world would be using in the mid-1990s by a factor of six, while leading studies in the early 1980s overestimated the cost of a barrel of oil by almost a factor of five (Lenssen and Flavin 1996, p. 770). These flawed estimates should remind us that our ability to project world energy supply and its composition and world energy demand and prices is very limited indeed in the intermediate and distant future. In the end, at what time and under what conditions solar energy complemented by other renewable energy sources will become widely available is contingent on our efforts in developing this renewable resource and in bringing its costs down. As early as 1952, the US President's Materials Policy Commission (1952b) called on the US to provide an outstanding contribution to world welfare by investing aggressively in the field of solar energy. More than half a century later, this call is still valid though now it is more about storage capacity, expanding and stabilising the electric grid, providing fast electricity charging stations, and investing aggressively in green hydrogen production.

So far, I have only dealt with energy resources. Whether solar energy and other renewable energy resources can substitute for non-renewable non-energy resources is even less clear. Direct substitution possibilities might be low, but a backstop energy technology has another advantage as well: if it provides services at very low cost, it can boost the availability of other resources that can be extracted economically – at least if one assumes that ever-lower-quality ores can be extracted with ever-rising energy and other inputs and that the costs of extraction do not rise steeply and quickly. It was this that Adelman (1990, p. 1) referred to in stating that 'the total mineral in the earth is an irrelevant non-binding constraint', for the question really is whether it will be possible or not to extract ever-more resources from ever-lower-quality ores at reasonable economic costs. Energy is the one and only real limiting factor in the long run because, given enough energy, there will always be enough natural non-energy resources extractable from the crust of the Earth.

However, there does not seem to exist any serious study that has tried to compute the prospects of backstop technologies to substitute on a large scale for the depletion of non-energy resources in the long run or to facilitate the mining of resource ores of low concentration. What we have are more or less optimistic statements, but no comprehensive, detailed analysis – see, for example, Gordon et al. (1987), Scott and Pearse (1992), Beckerman (1995) or Goeller and Zucker (1984) who assure the reader that they:

> believe that, with a few exceptions, the world contains plentiful retrievable resources that can supply mankind with the necessary materials for the very long term, and that these resources can probably be extracted and converted to useful forms indefinitely with acceptable environmental consequences and within the boundaries of foreseeable economic constraints. (Goeller and Zucker 1984, p. 456)

A more pessimistic view is taken by Ayres (2007, p. 126):

> while there is plenty of room for substitution and some possibility of major breakthroughs … the pessimists – those who espouse the notion of 'strong sustainability' appear to be closer to the truth than the optimists who believe in more or less unlimited substitution possibilities.

In Section 3.4 below, I will present evidence that suggests both non-renewable energy and non-energy resources have very large reserves, and there is no risk of running out of them any time soon.

3.2.2 The Role of Prices in Overcoming Resource Constraints

Now let us look at proposition (b). It highlights more than any of the other four propositions the role resource prices play in overcoming resource constraints. Prices serve different functions in an economy, the most important being that they signal economic scarcity and act as a coordination mechanism, pushing the economy towards efficiency and triggering technical progress. Resource pessimists have persistently either ignored or downplayed the role that prices play in easing resource constraints. It is naive, as, most famously, Meadows et al. (1972) have done in their *Limits to Growth* report, to compare current amounts of resource use with current proven reserves and simply extrapolate from the past that hence the resource will be depleted in *x* years. The gradual depletion of a resource affects its price, which affects supply and demand to which the economy adapts permanently. This dynamic process makes a mockery out of simple-minded static computations of a resource's remaining lifetime.

To highlight the role that prices play for resources, I will now introduce the famous Hotelling rule (Hotelling 1931). The rule states that, under some restrictive assumptions (on which more will be said later), the resource rent (that is, the price of the resource for the marginal unit minus the marginal cost for extracting this unit) in a perfectly competitive economy must rise at a rate equal to the interest rate for a given stock of a non-renewable resource, where the interest rate stands for a representative rate of return on alternative forms of investment.[5] The resource rent can be interpreted as the net marginal profit for the resource extractor and is often called 'Hotelling rent'. The rule holds true, with some amendments, for renewable resources as well – see Appendix 2, p. 179. Because of their much higher importance as an input into production, the analysis here refers solely to non-renewable resources.

The intuitive reason why the rule must hold in a context of rational utility-maximising agents is as follows: imagine otherwise, for example, that the resource rent rose at a rate lower than the interest rate. Then it would pay the resource owner to liquidate more of the resource, deposit his or her receipts in a bank, and earn interest on his or her account – which gives him or her a higher net rate of return than leaving the resource in the ground since, by assumption resource rents rise at a lower rate than the interest rate. It would pay to liquidate more of the resource until marginal extraction costs rise so much that the resource owner is just indifferent between extracting a marginal resource unit and leaving this unit in the ground. It might be profitable to even liquidate the whole resource stock! Now imagine instead that the resource rent rose at a higher rate than the interest rate. Then it would pay the resource owner to leave more of the resource in the ground in order to extract it later, thus getting a higher net rate of return than if he or she had extracted the resource right now and had put the receipts in a bank account. In other words, the Hotelling rule requires that the present value of resource rents is the same in all periods; that is, it is a profit-maximising condition of intertemporal arbitrage (Livernois 2008). The deeper reason why the Hotelling rule must hold is that for the resource owner, a stock of non-renewable resources is just another asset in his or her portfolio, so it must earn an equal net rate of return as the other portfolio assets do. Hence, equilibrium is where resource rent rises at a rate equal to the interest rate, where, to repeat, the interest rate stands for a representative rate of return on other assets rather than the interest one earns on depositing money in a bank account.

The following simple model derives the Hotelling rule:[6] a representative resource extracting firm maximises its profit π from a given resource stock S over an infinite time horizon. Assuming perfect competition, the firm takes the price P as given. The problem of the firm is to

$$\underset{R}{Max}\ \pi = \int_0^\infty \left\{ P(t)R(t) - C\left[R(t)\right] \right\} \cdot e^{-rt}dt \tag{3.1}$$

$$\text{s.t. } \dot{S}(t) = -R(t) \tag{3.2}$$

$$\text{and} \int_0^\infty R(t)\,dt = S(0) \tag{3.3}$$

where t is a time index, P the price of the resource, R the quantity of resource extracted at each instant of time, and C the total cost of extraction. r is the interest rate that is exogenously given to the model and used by the firm to discount future profits to their present value. That is, in equation (3.1), the firm chooses a suitable R that maximises the present (discounted) profit of the resource. Equation (3.2) is an equation of motion, where $S(t)$ is the total remaining stock of the resource at each instant of time, and the dot above S indicates the derivative of S with respect to t. Equation (3.2) simply states that the resource stock decreases by the amount of extraction. Equation (3.3) is an integral constraint that states that the integrated sum of all resource depletion should be equal to the initial resource stock $S(0)$. In other words, as time reaches infinity, the total stock should be exhausted, which is required by efficiency: the firm would forgo profits if it did not use up its stock.

The problem is solved by forming the Lagrangian Γ and maximising with respect to R:

$$\underset{R}{Max}\ \Gamma = \int_0^\infty \left\{ P(t)R(t) - C\left[R(t)\right] \right\} \cdot e^{-rt} dt - \lambda R(t) \tag{3.4}$$

where λ is the (constant) Lagrange multiplier. Assume the cost function to be 'well behaved', that is, strictly convex, continuous, and twice differentiable, so that $d^2C / dR^2 > 0$ and the necessary first-order condition is also sufficient for a maximum:

$$\left(P - \frac{dC}{dR} \right) = \lambda e^{rt} \tag{3.5}$$

Define H to be the resource rent:

$$H \equiv \left(P - \frac{dC}{dR} \right) \tag{3.6}$$

λ is constant for this so-called isoperimetric problem (Chiang 1992, pp. 139–43, 280–2). Differentiating (3.5) with respect to time and dividing the result by (3.5) leads to:

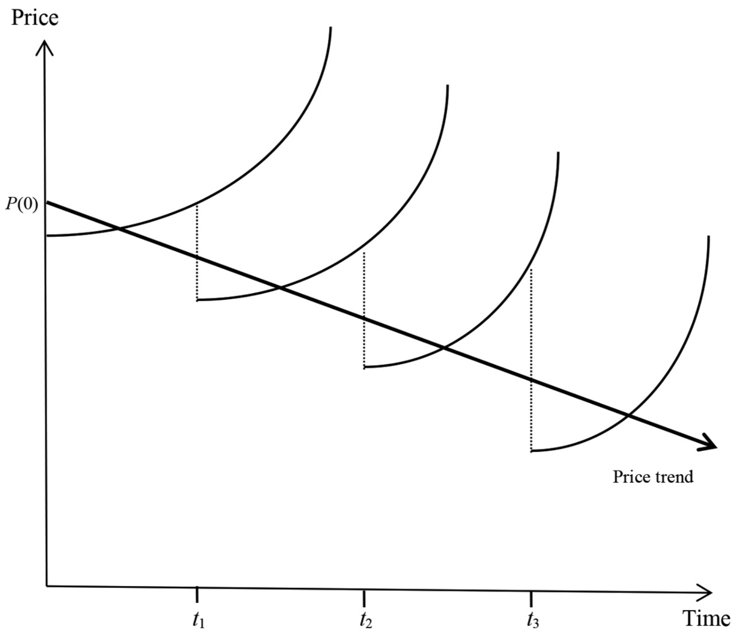
$$\frac{\dot{H}}{H} = r \tag{3.7}$$

that is, in the optimum the resource rent rises at the rate of interest (Hotelling rule). The basic result does not change if the firm maximises profits over a *finite* time period. Neither does the basic result depend on the firm being a price taker. If the firm is a price-setting monopolist, for example, it is marginal revenue minus marginal cost that rises at the interest rate and resource depletion is in general slower than under perfect competition (Pearce and Turner 1990, pp. 284–6). The form of market structure is of no further interest to the analysis here, however.

Unfortunately, resource rent is not directly observable and hence inherently difficult to measure. This is one of the reasons why attempts to empirically validate Hotelling's rule have resulted in contradictory findings – for an overview, see Berck (1995), Livernois (2008), Atewamba and Nkuiya (2017), and Ferreira da Cunha and Missemer (2020). More important than this, however, is that the resource rent rises at the interest rate only in a setting of certainty about, for example, the size of the resource stock, the date of exhaustion, the existence and marginal costs of a backstop technology, and so on, none of which exists in actual reality. Deshmukh and Pliska (1985) were one of the first to show that the resource rent need not rise at the rate of interest if uncertainty is introduced. Given the lack of certainty, exogenous unexpected shocks can result in deviations from the original price path in any direction, depending on the nature of the exogenous unexpected shock and its strength. There are myriad potential exogenous unexpected shocks, from unexpected new resource discoveries to unexpected breakthroughs in backstop technologies that can substitute for the non-renewable resource; from political crises and the eruption of wars that impact upon the supply of non-renewable resources to economic upheavals that change demand for the non-renewable resource; from unexpected changes to the real rate of return on investment to unexpected breakthroughs in drilling and mining technologies. An important one is new resource discoveries. Pindyck (1978) is the seminal paper showing how prices (and resource rent) can fall over time as the exploration of new unexpected and therefore hitherto unknown reserves increases the available resource stock.

To see this, look at the following very simple setting: assume that the marginal costs of resource extraction are constant and equal to zero. Before the discovery of new reserves, the resource stock was of size S. The resource rent had to increase at the rate of interest (equation 3.7) and economic efficiency demands that the stock is fully exhausted at time $t = \infty$ (equation 3.3), so the price P_0 that was initially set at time $t = 0$ is specified as well (see Figure 3.1).

As new reserves become known at time $t = t_1$, the available stock rises. The resource rent still must rise at the interest rate and economic efficiency still requires that the resource stock is fully exhausted at time $t = \infty$. But the available resource stock has increased, so it follows that the price set at time $t = t_1$ after the discovery of new reserves must lie below the price at time $t = t_1$ just before the discovery. That is, the price at time $t = t_1$ decreases because of the new discoveries. If new discoveries are frequent and large enough, the overall trend in the resource rent can be downward over time, as Figure 3.1 shows. Hence, actual resource rents might not only fail to rise at the interest rate, but may even fall over some time period if unexpected discoveries are made. Note that this does not contradict the Hotelling rule, which demands resource rent to rise at the interest rate only for a *given* stock of resources, that is, excluding newly discovered formerly unknown resources. And ultimately, of course, the Hotelling rent and therefore the resource price has to rise again because the total resource stock in the earth is finite.

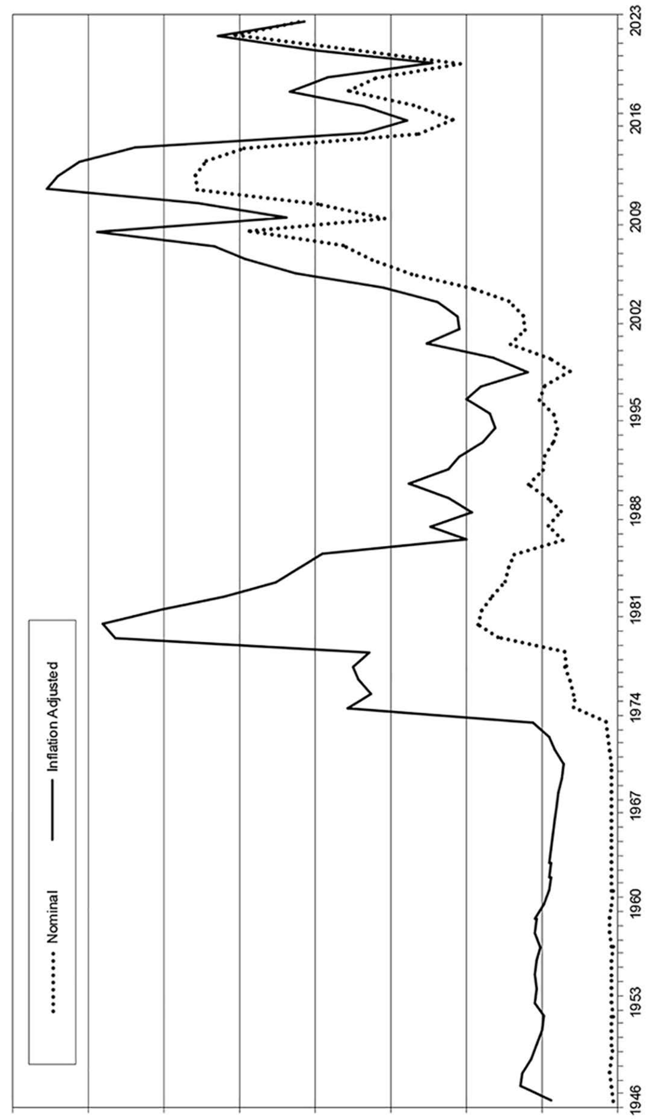


Source: Author.

Figure 3.1 Price path with frequent unexpected resource discoveries

I have derived this qualification to the Hotelling rule in a particularly simple context and looked at unexpected discoveries in an otherwise static environment. But the main result holds true for more complicated contexts as well (see Hartwick and Olewiler 1986; Perman et al. 2011, pp. 509–37): the resource rent is responsive to changes in the underlying economic scarcity of a resource, which suggests resource rent to be a good indicator of economic scarcity. The resource rent reflects the opportunity cost of current resource extraction, that is, the trade-off between resource extraction now and resource extraction in the future. It is a measure of anticipated scarcity of the resource. Rising resource rents would indicate rising scarcity, whereas falling resource rents would indicate falling scarcity, and no rise or fall would suggest no change in scarcity.

How has the price of the most important of non-renewable resources, oil, changed over time? Figure 3.2 shows both nominal and inflation-adjusted oil prices from 1946 to 2023, which reveals great volatility after 1970 in inflation-adjusted prices without a clear upward trend.



Source: Energy Institute (2024).

Figure 3.2 Crude oil prices per barrel of oil (1946 to 2023)

Can one conclude, therefore, that oil, as the quintessential non-renewable resource, has not become scarcer in an economic sense over the past and will not become scarce in the near future? Not necessarily so. There are two main caveats:

1. There exists a fundamental objection against using relative resource prices as an indicator for resource scarcity, as cogently articulated by Norgaard (1990, 1991). His argument is as follows: in an ideal system of complete markets, including futures and options markets, relative resource prices should reflect present and future scarcity accurately. The problem is that this full set of markets is non-existent and that, therefore, traders in natural resource markets have to form their own expectations about scarcity and future price paths. Since these traders are boundedly rational utility maximisers with imperfect information and imperfect foresight, they might well be badly informed about real resource scarcity. But if that is the case, then:

   > the cost and price paths their decisions generate are as likely to reflect their ignorance as reality. To control for whether or not allocators are informed, however, we would have to know whether resources are scarce. Since this is the original question, the exercise is logically impossible. (Norgaard 1990, pp. 19ff.)

   Inferring the real underlying scarcity trend from the time series of the indicator is therefore flawed from the beginning. Norgaard (1991, p. 195) suggests that the only thing one can really test is whether or not allocators *believe* that a resource is scarce and not real scarcity.
2. Past trends cannot simply be extrapolated into the future (and most definitely not into the far future). That the resource constraint is not binding yet does not imply that it will not be so in the future. Even if the global economy grew only modestly at a rate of 2 per cent per annum, world economic output would double approximately every 35 years. It is not all that clear whether there are sufficient resources for a quadrupling of global economic output. The point is that resource pessimists are concerned whether there will be enough resources in the future to satisfy a demand that tremendously exceeds past levels of demand.

Having said this, in Section 3.2.5, I will argue that existing evidence on non-renewable resource reserves suggests that one does not need to worry too much about the economic scarcity of these types of non-renewable resources. Further relief for non-renewable energy resources will additionally arise from the need to move away from carbon-containing fossil fuels like oil, gas, and coal towards renewable energy sources.

What about the prospects of recycling, that proposition (b) also refers to? These prospects are limited. Strictly speaking, given a backstop energy technology, the second law of thermodynamics imposes no strict physical constraint on the possibilities of recycling material. In principle, given an unlimited supply of energy, nearly all material could be recycled – a fact that follows directly from the first law of thermodynamics (conservation of mass) and that was initially denied by Georgescu-Roegen, but later accepted (Georgescu-Roegen 1986, p. 11). However, there is an economic constraint since, for many materials, the costs of recycling material are likely to become prohibitively high as the recycling rate tends towards 100 per cent. Recycling can ease a resource constraint for some time, but it cannot overcome it in the end.[7]

3.2.3 Substitution with Man-made Capital

Now let us turn to proposition (c). Evidently, proposition (a) cannot provide a satisfactory solution if there is no backstop technology that can substitute for all economically relevant resources, and substituting for them with renewable resources is either infeasible or would hugely overstretch their regenerative capacity. Equally, proposition (b) cannot be a satisfactory solution if we take on a very long-run perspective because, in the end, a non-renewable resource is just that: non-renewable, and it will be depleted in some finite time. The resource might still be substituted for with man-made capital then.

But can man-made capital substitute for an ever-diminishing natural resource stock? Solow (1974a) and Dasgupta and Heal (1979) have proved that, in theory at least, man-made capital can substitute for an ever-diminishing natural resource.[8] Dasgupta and Heal (1979) examine under which conditions a non-renewable resource is essential and when it is inessential, where an essential resource is defined as a resource for which 'feasible consumption must necessarily decline to zero in the long run' (p. 199). To make analysis possible, they must assume some sort of production function, and they take the constant elasticity of substitution (CES) production function, which is the most prominent production function in economics, for reasons of simplicity. Since they assume that labour is constant, one can also normalise it to 1 and suppress it, and put only man-made capital K and resource input R as arguments into the function. Hence, the constant elasticity of substitution refers to the elasticity of substitution between reproducible man-made capital and the non-renewable resource. Let us call this elasticity σ. The CES function can be represented as follows:

$$F(t) = \left\{ \alpha K(t)^{(\sigma-1)/\sigma} + \beta R(t)^{(\sigma-1)/\sigma} + (1-\alpha-\beta) \right\}^{\sigma/(\sigma-1)} \qquad (3.8)$$

where F is produced output and $\alpha, \beta > 0$, $\alpha + \beta < 1$, and[9]

$$\sigma = \frac{d\ln\left(K/R\right)}{d\ln\left|MRS_{K,R}\right|} \Rightarrow \sigma \geq 0 \tag{3.9}$$

where MRS is the marginal rate of substitution between K and R:

$$MRS_{K,R} = \frac{dK}{dR} = -\frac{\partial F/\partial R}{\partial F/\partial K} = \frac{P_R}{P_K} \tag{3.10}$$

and P_K, P_R is the price of the man-made capital factor and resource factor price, respectively. The higher is σ, the better can resources be substituted with man-made capital. There are three cases to distinguish: first, $\sigma > 1$; second, $\sigma = 1$, and, third, $\sigma < 1$.

The first case is trivial and therefore uninteresting. To see this, note that with $\sigma > 1$ all exponents become greater than zero and since resources enter the production function only in an additive way, they are inessential. However, for the same reason it is possible to have $F(K,0) > 0$, that is, production without any input of resources, which contradicts the first law of thermodynamics. That something can be produced without any resource input is a physical impossibility. $\sigma > 1$ can therefore be dismissed.

The third case is uninteresting as well. Note that for this case, the average product of the resource, *F/R*, is

$$\frac{F(t)}{R(t)} = \left\{\alpha K(t)^{(\sigma-1)/\sigma} + \beta R(t)^{(\sigma-1)/\sigma} + (1-\alpha-\beta)\right\}^{\sigma/(\sigma-1)} R(t)^{-1} \tag{3.11}$$

or equivalently

$$\frac{F(t)}{R(t)} = \left\{\alpha\left(\frac{R(t)}{K(t)}\right)^{(1-\sigma)/\sigma} + \beta + (1-\alpha-\beta)R(t)^{(1-\sigma)/\sigma}\right\}^{\sigma/(\sigma-1)} \tag{3.12}$$

and it is bounded above as the resource becomes depleted, because as $R \to 0$, *F/R* becomes

$$\lim_{R\to 0} F(t)/R(t) = \beta^{\sigma/(\sigma-1)} \tag{3.13}$$

With a finite resource stock and no technical progress, the boundedness of the average product *F/R* implies that total output is finite, so that output must decline to zero as time approaches infinity. In the limit with $\sigma = 0$ the CES function degenerates into a so-called Leontief production function of the form $F(K,R) = \min(vK, wR)$ with $v > 0, w > 0$, which means that all substitution possibilities are ruled out and we reach perfect complementarity (Varian 1992, p. 20).

In the second case, with $\sigma = 1$ the CES function is formally undefined but can be shown to collapse into a function that is known by economists as the Cobb–Douglas production function (Chiang 1984, pp. 428ff.). It takes the following form:

$$F(t) = K(t)^{\alpha} \cdot R(t)^{\beta} \tag{3.14}$$

It is apparent that the resource is not trivially inessential, since without resources ($R = 0$) no production is possible, that is, $F = 0$. However, dividing F by R and taking the partial derivative of F with respect to R shows that

$$\max_{R} \Gamma = \int_0^{\infty} \left[P(t)R(t) - R(t)C(0) \cdot e^{-kt} \right] \cdot e^{-rt} dt - \lambda R(t) \tag{3.15}$$

so for $\sigma = 1$ both the average (*F/R*) and marginal product $\partial F / \partial R$ of the resource are unbounded and both *F/R* and $\partial F / \partial R \to \infty$ as $R \to 0$. This combination ensures that the case $\sigma = 1$ is non-trivial: it is not a priori clear whether the resource is essential or not. Dasgupta and Heal (1979, pp. 200–5) prove that the resource is not essential if $\alpha > \beta$, that is, if the elasticity of output with respect to man-made capital is higher than the elasticity of output with respect to the non-renewable resource. There is no direct intuition for this result beyond the mathematical necessity. However, since in a competitive economy these elasticities are equal to the share of total income going to the factors man-made capital and resources, respectively (Euler's theorem), Dasgupta and Heal (1979, p. 200) circumscribe the condition $\alpha > \beta$ with the condition that man-made capital is 'sufficiently important in production'. Solow (1974a, p. 39), Hartwick (1977, p. 974), and Dasgupta and Heal (1979, p. 205) suggest that man-made capital's share is as much as four times higher than the share of resources, so that resources are not essential for the Cobb–Douglas case.[10]

There are several objections, however, that can be raised against being optimistic as a consequence of this analysis:

1. The first objection is that we do not know whether σ is greater than, equal to, or smaller than 1, even if we exclusively focus on the issue of whether man-made capital can substitute for non-renewable energy resources in

the production function. Early studies from the 1970s and 1980s arrived at 'notably contradictory' (Solow 1987, p. 605) findings. More recent review studies have pointed to the conceptual and econometric difficulties encountered in trying to estimate σ. With this caveat in mind, Markandya and Pedroso-Galinato (2007) come to the conclusion in their cross-national study that their estimates of the elasticity of substitution between energy resources and other inputs tend to be generally high. A similar summary view is reached by a meta-analysis (a study of studies) by Koetse et al. (2008). By contrast, Cohen et al. (2019) review all the existing literature and come to the sobering conclusion that 'substitutability between energy … and other forms of capital can only be plausibly low to moderate' (p. 442). Given these contradictory findings, one cannot have much confidence that non-renewable energy resources and man-made capital are highly substitutable.

2. The second objection is that we cannot rule out the possibility that σ becomes smaller than 1 as more and more of the resource is used up. That is, σ is not constant over time, but is itself a function of time, that is, $\sigma = \sigma(t)$. Dasgupta and Heal assume a CES production function for simplicity, but there is no reason to expect that in reality the elasticity of substitution between man-made capital and resources is constant over time. As Dasgupta and Heal (1979, p. 207) remark themselves, constancy might be a flawed assumption as the resource is run down and the ratio of man-made capital to resources becomes very high. This could be the case especially in that phase, even assuming $\sigma = 1$ might contradict physical laws, since it assumes that F/R and $\partial F / \partial R \rightarrow \infty$ as $R \rightarrow 0$; that is, the average product and the marginal product of the resource tend towards infinity as the resource stock tends to zero.
3. The third objection applies the same kind of argument to the share of man-made capital and the resource share of total income. There is no reason to expect that, in reality, those shares remain constant as the stock of the resource tends towards depletion (Slade 1987, p. 351). α and β are not constant over time, but are functions of time, that is $\alpha = \alpha(t)$ and $\beta = \beta(t)$. Hence, even if σ was constantly equal to 1 throughout, the elasticity of output with respect to the resource $\beta(t)$ might supersede the elasticity of output with respect to man-made capital $\alpha(t)$, after which the resource will become essential.
4. The fourth objection is that the dichotomy of man-made capital versus resources is an artificial and flawed one since man-made capital consists partly of resources. Victor (1991) looks at the properties of a Cobb-Douglas production function if it is assumed that man-made capital is itself produced from man-made capital, resources, and labour. Let the production function F be of the form[11]

$$F = K^c R^d L^e \text{, with } c, d, e > 0 \text{ and } c + d + e = 1 \tag{3.16}$$

Now let the production function for producing man-made capital be of the form

$$K = K^p R^q L^s \text{, with } p, q, s > 0 \text{ and } p + q + s = 1 \tag{3.17}$$

Solving (3.17) for K gives

$$K = R^{\left(q/1-p\right)} L^{\left(s/1-p\right)} \tag{3.18}$$

Substituting (3.18) into (3.16) and rearranging, we arrive at

$$F = R^{\left(\frac{c \cdot q}{1-p}+d\right)} L^{\left(\frac{c \cdot s}{1-p}+e\right)} \tag{3.19}$$

It is obvious that man-made capital can no longer infinitely substitute for an ever-declining resource stock. Of course, resources might still be substituted for by an ever-increasing labour input; but, in contrast to man-made capital, labour is not a factor that can be increased indefinitely since labour is supplied by human beings. That is, in effect, given that resources are needed for the production of man-made capital, resources become essential for production, even for the Cobb–Douglas case: man-made capital cannot infinitely substitute for vanishing resources.

Note, however, that just because substitution possibilities are restricted, this does not imply that R and K are complements, as Daly (1995a, p. 51) erroneously suggests when he argues as follows:

> Manmade capital is itself a physical transformation of natural resources which are the flow yield from the stock of natural capital. Therefore, producing more of the alleged substitute (manmade capital), physically requires more of the very thing being substituted for (natural capital) – the defining condition of complementarity.

The first part of this argument is undoubtedly correct because it follows from the first law of thermodynamics (conservation of mass). However, the problem with the second part of the argument is that the conclusion ('complementarity') does not follow from the correct observation. In economic terms, perfect complementarity is defined as a limitational production function of the form $F\left[K\left(R\right),R\right] = min\left(vK, wR\right)$, with $v > 0$, $w > 0$ being parameters and isoquants that look like rectangles. In other words, increasing man-made capital input in the production process for output does not increase output if resource input is not increased at the same time. Daly (1995a, p. 55) accepts this definition. However, the simple fact that one input into the production of man-made capital is natural capital does not imply complementarity thus defined.

One can show this both for the case that the economy is on the production possibility frontier and for the case that it is not. Let us start with the latter case first. Assume an economy with an endowment of five units of man-made capital and 10 units of resources. Assume for simplicity that each unit of capital together with two units of resources produces exactly one unit of the consumption good. Further, assume that man-made capital and resources are perfect substitutes in the production of the consumption good; that is, instead of using 10 units of resources and 5 units of capital to produce 5 units of the consumption good, one could also use 10 additional units of capital to substitute for the resource. Assume, however, that the production of each capital good itself requires 0.5 units of natural resources. Now, produce 10 additional units of the capital good to substitute for the 10 units of resources in the production of the consumption good. Since the production of each unit of capital requires only 0.5 units of natural resources, total resource input has decreased by 5 units. These 5 units could be used to increase production. It follows that $K = K(R)$ does not imply that output cannot be increased without increasing resource input at the same time.

Of course, as soon as all resources have been substituted for in the production of the consumption good, then, in the absence of technical progress, there is no longer leeway for substitution since the resource requirement for the production of the capital good is presumed to be fixed; that is, with $K = K(R)$, it is not possible to increase production indefinitely while at the same time driving resource use down to zero. This is the case of the economy being on the production possibility frontier. By assumption, all the available resources are in efficient use and output cannot be increased further. However, for this case as well, Daly's argument is not correct: the pure fact that resources are needed for the production of man-made capital ($K = K(R)$) does not imply anything for the shape of the isoquants in the production function for the consumption good and therefore does not imply that $F\left[K\left(R\right),R\right] = min\left(vK,wR\right)$. As Pearce (1997, p. 296) points out, if Daly's argument was valid then all forms of capital would be complements to each other since all forms of capital embody, to some extent, other forms of capital as well.

Daly (1994, p. 25) provides another general argument with which he tries to refute the possibility of substituting man-made capital for natural capital (here: natural resources):

> One way to make an argument is to assume the opposite and show that it is absurd. If man-made capital were a near perfect substitute for natural capital, then natural capital would be a near perfect substitute for man-made capital. But if so, there

would have been no reason to accumulate man-made capital in the first place, since we were endowed by nature with a near perfect substitute.

This second argument is also incorrect, however. It says that if A is a near-perfect substitute for B, then B must be a near-perfect substitute for A. However, the conclusion does not follow from the premise. A might have some additional desirable properties that B does not have: for some production purposes, A and B are almost near-perfect substitutes with almost linear isoquants. But for other purposes, A has some desirable properties that B does not have. Hence, A can substitute for the totality of B, but not vice versa. Hence, there is reason to accumulate A and substitute for B.

3.2.4 Technical Progress

Let us finally turn to proposition (d). Technical progress can be divided into what economists call 'resource-augmenting' technical progress and what I call 'augmenting-resource' technical progress for lack of a *terminus technicus*. Resource-augmenting technical progress increases the efficiency of resource use and means that ever-more output can be produced from a given stock of resources or that, conversely, for a given output ever-less resource input is needed. 'Augmenting-resource' technical progress reduces resource extraction costs, which means that lower-quality ores of a resource or resource deposits that were hitherto not profitably extractable now become economical to extract. This implies that the economically relevant resource stock *increases*, although the total physical stock of a finite non-renewable resource cannot be increased, of course. It is this that Baumol (1986) had in mind when he spoke of 'the possibility of continuing expansion of finite resources'.

In many ways, technical progress is the strongest proposition of the resource optimists. Let us turn to resource-augmenting technical progress first. It is easy to see that if there is permanent resource-augmenting technical progress, that is, if a unit of output can be produced with ever-declining resource inputs, then the resource will never be fully exhausted. Assume, for example, that there is exponential resource-augmenting technical progress. The production function now looks like:

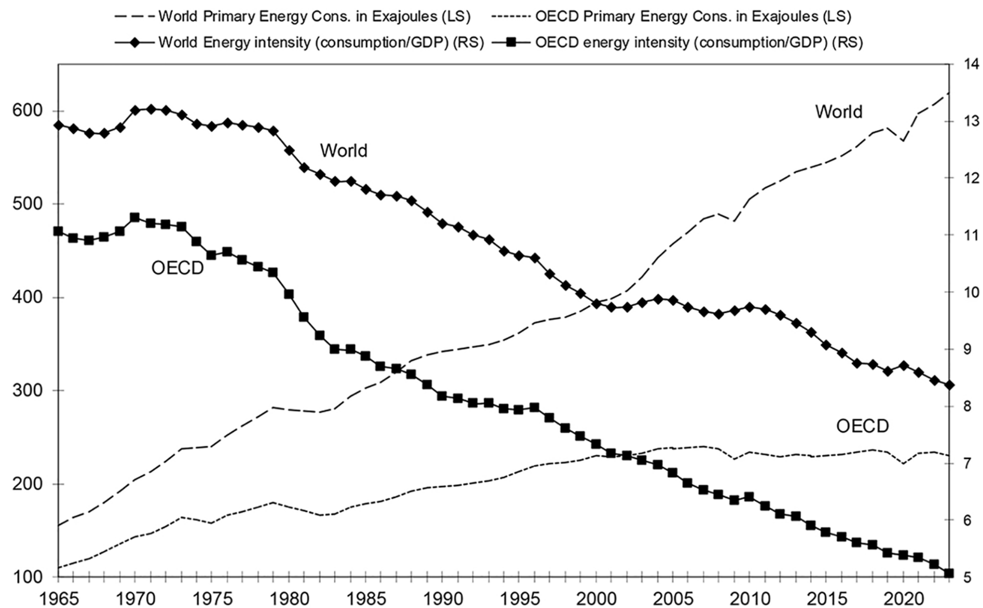
$$F = F\left[K(t), R(t) \cdot e^{kt}\right] \tag{3.20}$$

with k as the rate of technical progress. Permanent resource-augmenting technical progress can now compensate for an ever-diminishing natural resource stock. The same holds true as Stiglitz (1974) proves for so-called Hicks-neutral technical progress, that is, technical progress that cannot be attributed to a production factor, if:

- the production function is Cobb–Douglas, that is $\sigma = 1$,
- and m / β is sufficiently large, where m is the rate of Hicks-neutral technical progress and β is the income share of the resource, so that m / β can be loosely interpreted as the rate of resource-augmenting technical progress (Toman et al. 1995, p. 145).

But how realistic is this? Whether permanent resource-augmenting technical progress is possible, especially in the limit as resource stocks go down, is unclear. Ayres and Miller (1980) and Gross and Veendorp (1990) suggest that assuming so contradicts the first law of thermodynamics (conservation of mass). Dasgupta (2008) does not go this far but finds it hard to give credence to the idea that technological progress can substitute for a permanently vanishing natural resource base. There are likely to be limits to increasing efficiency. While it might be possible to reduce the required resource input per unit of output by a factor of, say, 10 or sometimes even 100 for most resources, it is presumably technically not possible to increase efficiency by a factor of 1000 or more.

Unfortunately, it is rather difficult to measure resource-augmenting technical progress. Take energy use as an example. Figure 3.3 shows the time trend in energy intensity for the world and for OECD countries (the group of high-income developed countries of the 'Global North'). Energy intensity is the ratio of energy input expressed in physical terms to the inflation-adjusted value of economic output, usually GDP.[12] The problem with this measurement is that it does not directly measure changes in the technical energy efficiency of production, which is what we are looking for when we want to measure resource-augmenting technical progress. A decline in the energy intensity of an economy can come about for a number of reasons other than technical progress itself: for example, because of a change in the sectoral structure of the economy; because of the substitution of labour or man-made capital for energy; because of a change in the energy input mix towards energy sources which can provide more useful work per unit of heat, and so on. Conversely, technical progress can be stronger than declining trends in the energy intensity of the economy suggest if consumption patterns shift over time to more energy-intensive goods and services, for example, from bicycles to motorcycles and then automobiles as the dominant mode of transport. Similarly, as economies become richer, the access of average households to energy-consuming appliances like washing machines, dishwashers, air conditioning, television, computers, and so on increases. With these caveats in mind, the reductions in



Note: Primary energy consumption in million tonnes oil equivalent on the left-hand scale. Energy intensity (consumption/GDP • 10^4) on the right-hand scale.
Source: Energy Institute (2024) and World Bank (2024).

Figure 3.3 Energy consumption and energy intensity (1965 to 2023) energy intensity shown in Figure 3.3 have not been very impressive, particularly given the very long time period covered. The world's energy intensity decreased by approximately 35 per cent from 1965 to 2023. The reduction in energy intensity of OECD countries is somewhat larger, at 54 per cent, but still somewhat modest. Much, much larger reductions in energy intensity would be needed for resource-augmenting technical progress to prove the resource optimists right.

Another caveat when inferring conclusions from looking at resource-augmenting technical progress is that even if resource intensity falls over time, *absolute* resource consumption may still rise if the rate of resource consumption growth is higher than the rate of resource-augmenting technical progress. Looking again at Figure 3.3 it is clear that while energy intensities have fallen over time both worldwide and for the OECD countries, consumption of primary energy has continuously risen due to tremendous population and economic output growth. The size of the world population stood at around 3.3 billion people in 1965 but was just above 8 billion people in 2023, according to the United Nations Population Division.[13] The world economy, meanwhile, grew from about US$14.32 trillion in constant 2015 prices in 1965 to circa US$92.83 trillion in 2023, according to the World Bank.[14] World population has thus increased by around 240 per cent over this period, while world GDP in 2023 is more than six times larger than it was in 1965. And while, according to the 2024 projections by the UN Population Division, world population will 'merely' be expected to grow by another 2 billion people or so and then peak at around 10.3 billion people around the mid-2080s and then start to fall slightly for the rest of this century, there is no reason why world GDP could not, in principle, keep growing and thus, all other things equal, keep on significantly increasing world energy consumption.

In fact, falling energy intensity and rising absolute energy consumption are even more closely related: resource-augmenting technical progress reduces the implicit price of energy, thus making production cheaper, boosting production and favouring the substitution of energy for other factors of production, which in return implies, *ceteris paribus*, an increased demand for energy (Brookes 1990, 1992; Binswanger 2001). Khazzoom (1987) and Brookes (1990, 1992) believe that this 'rebound' effect will in most cases be strong enough to lead to a *net* increase in energy use (the so-called 'backfire effect', which is a rebound effect that is larger than 100 per cent in magnitude).[15] Howarth (1997, p. 8) argues, however, that this conjecture will only hold true under the conditions that '(i) energy accounts for a large fraction of the total cost of energy services and (ii) the production of energy services constitutes a substantial fraction of economic activity'. He finds that neither of these conditions is empirically plausible. Gillingham et al. (2016) find no evidence in the empirical literature supporting the 'backfire effect'. That said, rebound effects smaller than 100 per cent, where the 'backfire effect' starts, are likely to exist even if estimating their exact magnitude proves exceedingly difficult (Stern 2020).

Let us now turn to 'augmenting-resource' technical progress.

Using the simple model I introduced in Section 3.2.2, p. 59, one can show how the resource price can fall over time given sufficient progress in resource-extraction technology. Assume that there is exponential technical progress at a constant rate k so that resource-extraction costs develop according to $C(t) = C(0) \cdot e^{-kt}$. The new problem facing the competitive resource-extracting firm is to

$$\max_{R} \Gamma = \int_{0}^{\infty} \left[P(t) R(t) - R(t) C(0) \cdot e^{-kt} \right] \cdot e^{-rt} dt - \lambda R(t) \qquad (3.4')$$

which has the first-order condition

$$P = \lambda e^{rt} + C(0) \cdot e^{-kt} \qquad (3.5')$$

Differentiating (3.5′) with respect to time leads to (λ constant)

$$\dot{P} = r\lambda e^{rt} - kC(0) \cdot e^{-kt} \qquad (3.6')$$

Both terms on the right-hand side of (3.6′) are positive. The second term is increasing in k (for $0 < k < 1$), hence (3.6′) can become negative if k is sufficiently large: resource prices can fall if technical progress is sufficiently strong.

Technical progress can boost the economically relevant resource stock and ease the resource constraint over a significant time span. Technical progress has made offshore oil and gas exploration from platforms that float on the seawater surface economically attractive. Horizontal drilling and hydraulic fracturing techniques have made hitherto unavailable oil, as well as shale gas deposits, available in many countries of the world. However, whether there will be, and can be, permanent and ideally exponential technical progress is unclear. That there has been enormous technical progress in the past is beyond doubt, but there is no assurance that there will also be permanent technical progress in the future. Already in 1975, Lecomber (1975, p. 45) hit the nail on the head: 'The central feature of technical advance is indeed its uncertainty.' It all boils down to whether one believes strongly in technical progress or not. Clearly, resource optimists have this strong faith in technical progress. It is worth quoting an even earlier source, namely, Beckerman (1972, p. 338), at some length here:

> In fact, given the natural concentrations of the key metals in the Earth's crust as indicated by a large number of random samples the total natural occurrence of most

> metals in the top mile of the Earth's crust has been estimated to be about a million times as great as present known reserves. Since the latter amount to about a hundred years' supplies this means we have enough to last about one hundred million years. Even though it may be impossible at present to mine to a depth of one mile at every point in the Earth's crust, by the time we reach the year A.D. 100,000,000 I am sure we will think up something. If the idea that actual reserves might be a million times currently proved reserves seems unbelievable it should be borne in mind that existing proved reserves are probably about a million times as big as those known in the days of Pericles.

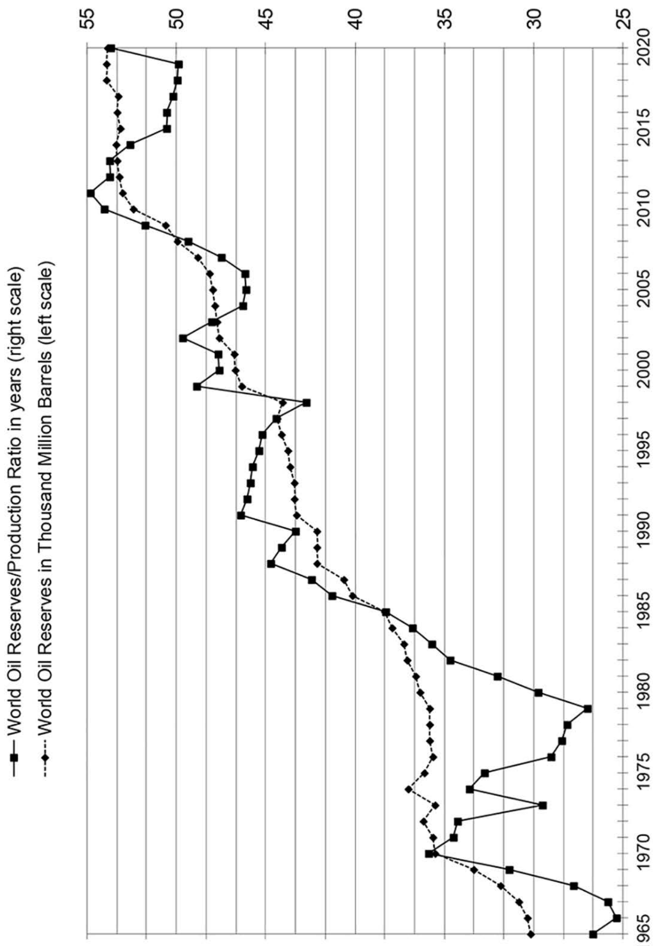
This is resource optimism in its purest form, but it is also pure speculation. We simply cannot rely on Beckerman's faith holding true.

3.2.5 Empirical Evidence

The world economy has, so far at least, exhibited a most remarkable capability to overcome resource constraints via substitution and technical progress. Reserves of both energy and non-energy resources have, by and large, persistently increased over time despite decades of large amounts of resource extraction. Figures 3.4 and 3.5, respectively, show the trend in world oil and gas reserves from 1965 (oil) or 1970 (gas) to 2020. They also show their static reserves index, that is, the reserves to production ratio in years, which measures for how many years reserves in a particular year would last at the same rate of production as of that year. For both oil and gas, both absolute reserves and the static reserves to production ratio are much higher in 2020 than in 1965 (oil) or 1970 (gas), respectively.

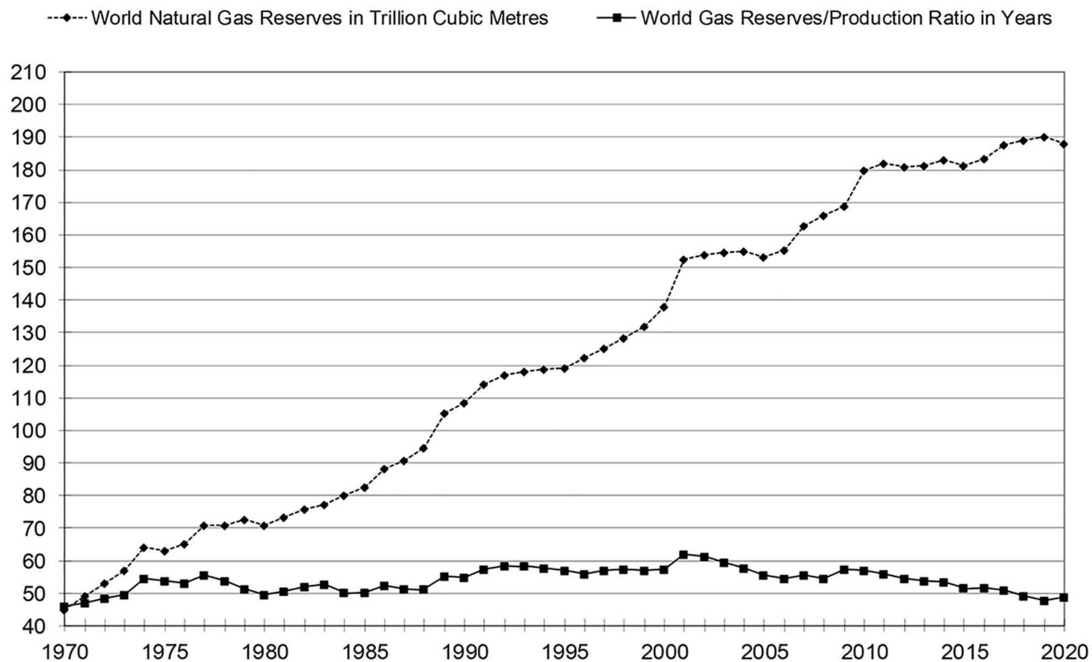
One needs to interpret these figures with some caution, however. First, there are incentives for countries to over-report reserves (Sauré 2008). Looking in more detail at the reserve figures of oil exporters, particularly of member countries of the Organization of Petroleum Exporting Countries (OPEC), reveals that, at times, reserves have miraculously shot upward when it was politically convenient for these countries. Second, the reserves to production ratio seemingly suggests that oil wells can be exploited at the same rate until the last drop has been taken out. However, oil extraction from a well typically follows a logistic curve in which maximum or peak extraction is reached when half of the well has been exhausted. Nevertheless, and keeping these caveats in mind, reserves have clearly more than kept up with production.

In fact, resource optimists' arguments that there are sufficient reserves are strengthened by the transition away from fossil fuels towards non-carbon-emitting renewable energy sources. In its 2023 World Energy Outlook, the International Energy Agency (2023) makes the following bold statement: 'We are on track to see all fossil fuels peak before 2030.' Of course, this is a highly



Source: Energy Institute (2024).

Figure 3.4 World oil reserves (1965 to 2020)



Source: Energy Institute (2024).

Figure 3.5 *World natural gas reserves (1970 to 2020)* contested statement to make, and predictions about peak oil (and other fossil fuels) have repeatedly been proven wrong in the past (Smil 2006).

Besides conventional oil reserves, there are also unconventional ones, from the Canadian province Alberta's oil sands, to the heavy oil deposits in the Orinoco River in Venezuela, to deep sea oil fields below salt deposits several hundred metres thick offshore in Brazil and other places. One of the major technological breakthroughs over the past decades has been the development of technologies such as horizontal drilling and hydraulic fracturing, which can extract at economic profit these unconventional oil and natural gas reserves.

In sum, the world has such large reserves, both conventional and unconventional, of oil and gas, not to speak of coal, that there is no risk of running out of them any time soon. This holds even if the poorer countries continue to economically catch up with the high-income countries, which means that their economies grow faster than richer ones (Cole and Neumayer 2003), which typically results in strong growth in their non-renewable resource consumption. In fact, there are such large reserves of fossil fuels that extracting them all would create absolute havoc with the global climate. As Helm (2011, p. 89) has put it: 'The danger is now that we have far too much oil, gas, and coal, not too little, for the climate to tolerate.'

What about non-energy non-renewable resources? Table 3.1 presents the reserves to production ratio for selected non-energy resources in 2023 together with the 'resource' to production ratio, where 'resource' here is defined by USGS (2024, p. 207) as 'a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible'. In other words, whereas reserves cover the remaining stock that is currently economically extractable, that is, extractable at a profit with current technology, the 'resource' covers that remaining stock that is potentially economically extractable. For many resources, reserves are plentiful and there is no apparent risk of running out of these non-energy non-renewable resources. For some others, such as chromium, lead, nickel, tin, and zinc, the reserves to production ratio is not very high but the 'resource' to production ratio is very high. All the available evidence so far therefore seems to strongly support the substitutability assumption of WS with respect to natural capital as an input to the production of goods and services.

What about water and food resources? Essentially, from a pure resourcing perspective, the problem in each of these is predominantly one of access, which is a function of economic resources and having the power to purchase water and food, rather than physical limits. With enough energy input, drinkable water can always be gained by desalination or by treating and cleaning water from rivers or even from discharged water. It can also be pumped or transported from elsewhere where water is more plentiful.

Table 3.1 *Availability of key non-energy non-renewable resources*

Resource	Static Reserves to Production Ratio	Static 'Resource' to Production Ratio
Bauxite	75	138
Chromium	14	>1000
Cobalt	48	109
Copper	45	95
Gold	20	n.a.
Iron ore	5800	15333
Lead	21	444
Lithium	156	583
Manganese	95	large
Nickel	36	97
Phosphate rock	336	>1000
Platinum-group metals	145	204
Potash	92	>1000
Rare earths	314	large
Silver	23	n.a.
Tin	15	large
Zinc	18	>1000

Note: Ratio expressed in years. 'Large' means quantity unknown but typically sufficient for centuries to come.
Source: USGS (2024).

To feed more people, there are multiple strategies. One is extensification, that is, using more land for agriculture. Note, however, that existing agriculture already uses up about one-third of the planet's non-glaciated land (Smil 2023, p. 174). By contrast, chemical inputs used in agriculture to make it more productive per unit of land used, such as nitrogen, potassium, and phosphorus, are abundantly available (p. 175). More efficient farming practices, reduced food waste, and a diet of more moderate meat consumption present other more conventional strategies. Vertical farming, as well as artificial meat production in laboratories, present more unconventional strategies that have not yet been fully explored, let alone deployed on a significant scale.

In any case, the availability of food is more a problem of intra-generational and intra-national distribution than a question of inter-generational sustainability. This finding is supported by those who have studied the political economy of famines and hunger (Drèze and Sen 1989; Drèze et al. 1995; Plümper and Neumayer 2009). Of course, climate change can significantly exacerbate any regionally or locally felt water or food shortages or any shortages experienced by certain groups of people within certain locations. In their meta-analysis of studies looking at projected global food demand as well as the population at risk of hunger for the period 2010 to 2050, Van Dijk et al. (2021, p. 494) come to the conclusion that despite food demand being expected to increase by between 35 per cent and 56 per cent between 2010 and 2050, the projected population at risk of hunger is expected to change by between -91 per cent (that is, significantly shrink) and +8 per cent (increase slightly). The upper estimate increases to +30 per cent if climate change is taken into account. (They also state that the difference is not statistically significant, but that does not mean it is non-existent.)

Of course, the assessment presented above only looked at the global availability of natural resources. It has not engaged with the fact that these resources are often very unevenly distributed across the world, which raises geopolitical and national security interest concerns as well as concerns about market power, with OPEC only being the most salient and well-known aspect of this. These concerns are beyond the scope of this book, however.

Similarly, so far in this chapter, I have not addressed the significant to massive environmental damages generated in the process of extracting these resources or consuming them. Likewise, I have not addressed how resourcing water from desalination plants may result in environmental pollution or how agricultural food production may result in soil degradation, the lowering of water tables, water pollution, species loss, and ecosystem destruction. These are all part and parcel of the remainder of this chapter, which addresses environmental degradation, as does Chapter 4.

3.3 ENVIRONMENTAL DEGRADATION

As just mentioned, so far I have only looked at the 'source' side of the economy. Now I take a look at the 'sink' side of the economy and environmental degradation.[16] In reality, of course, there is no such strict dichotomy between both aspects since a renewable resource that becomes exhausted while being used in production might have provided other environmental amenity functions for human beings as well; or the mining of non-renewable resources produces environmentally detrimental side effects, as is the case in extracting bauxite for the production of aluminium, or in drilling, refining, and processing oil.

To start with, I will analyse, in Section 3.3.1, whether future generations can be compensated for long-term environmental degradation via increased consumption. The paradigm of WS is built on the assumption that increases in man-made and human capital can compensate future generations for deteriorations in natural capital – less of it or lower quality. One can therefore make the argument that rising consumption of goods and services, which typically comes with increases in man-made and human capital, can compensate future generations for an increasingly degraded environment, whereas SS, as defined in Section 2.3.2, denies this possibility. The argument that rising consumption can compensate, without limit, for environmental degradation is difficult to maintain, however. Proponents of WS are therefore more likely to argue that while some form of an increase in environmental degradation may be inevitable in the short to medium term, eventually the economic growth that comes with increases in man-made and human capital will be good for the environment and will result in an improved rather than degraded environment. I therefore discuss the impact of economic growth on the environment in some detail in Section 3.3.2, assessing whether this environmentally optimistic view of WS proponents is more persuasive than the environmentally pessimistic view of SS proponents who tend to argue that economic growth is unambiguously harmful for the environment.

3.3.1 Can Future Generations Be Compensated for Environmental Degradation?

The problem with assessing the question of whether future generations can be compensated for long-term and large-scale environmental degradation is that one has to rely on speculation, since we cannot know how future generations will value consumption goods and services relative to the utility derived from the whole range of environmental services. It seems safe to assume that all individuals, independent of the generation they belong to, share the same basic needs and wants (such as clean water, food, shelter, breathable air, a bearable climate, as well as basic enjoyments such as being able to access greenspaces, and so on). There is mounting evidence that the ability of people to experience nature and access greenspaces significantly improves their health and well-being (Willis 2024). One might want to argue, therefore, that ever-rising consumption of goods and services cannot compensate for the extinction of all renewable resources and for ever-rising pollution since this would most likely endanger the satisfaction of basic needs and wants. Barry (1991, p. 248) argues that while ‘it is true that we do not know what the precise tastes of our remote descendants will be, they are unlikely to include a desire for skin cancer, soil erosion, or the inundation of all low-lying areas as a result of the melting of the ice-caps’.

It does not follow, however, that all environmental damage has to be avoided, and that consumption growth cannot compensate for environmental degradation to a certain extent and within certain limits. The problem with Barry’s argument is that, taken to its logical conclusion, it would imply that the current generation must not impose any environmental harm on the future. However, such a prescription carries with it a tremendous opportunity cost. The world we live in is full of trade-offs. As I will argue in Section 4.5, p. 121, there are no easy answers to how to deal with these trade-offs. But, as will be argued in more detail there, ignoring the existence of fundamental trade-offs is not appropriate.

One would want to ask future generations which harm they regard as not amenable to compensation by increased consumption opportunities. Since this is impossible, one could ask members of the current generation. There is some evidence that a minority of people express preferences in contingent valuation (CV) studies that can be argued to be consistent with what is known as lexicographic preferences (Stevens et al. 1991; Spash and Hanley 1995; Hanley and Milne 1996; Foster and Mourato 2000): they prefer natural capital protection independently of the cost of doing so and no increase in consumption can compensate them for a degradation in natural capital. However, Veisten et al. (2006) show that what appears as lexicographic preferences at first sight often represents nothing else but simply high valuation for the environmental good, concluding that 'people with lexicographic preferences for biodiversity are probably less numerous than previously indicated' (p. 167). Sælensminde (2006) argues that often what might appear to be lexicographic choices need not imply lexicographic preferences since the apparently lexicographic choices are driven by study designs in which the differences between alternatives offered are too great and the choice task is overly simplified. Drupp (2018, p. 151) in his review of existing studies finds that 'empirical evidence on the substitutability parameter suggests that most ecosystem services are considered highly substitutable by manufactured goods'.

Be that as it may, it is fair to say that proponents of SS typically reject compensability mainly for normative reasons. In other words, consumption growth *should* not be allowed to compensate for future environmental degradation. The proposition would therefore not be refuted by the fact that empirical evidence for existing lexicographic preferences is rather weak in contingent valuation studies, not least because proponents of SS typically reject the notion that these studies can truly recover environmental values (Spash 2022).

In conclusion, the proposition of SS that natural capital should in principle be regarded as non-substitutable as a direct provider of utility and that therefore increased consumption cannot compensate for environmental degradation seems hard to defend if it is taken as a *positive* position (that is, as the position that people unambiguously reject the possibility of compensating them for environmental degradation by increased consumption) and is non-refutable if it is taken as a *normative* position (that is, as the position that people *should* reject compensation for environmental degradation by increased consumption).

On the other hand, presumably not many people will find the opposite extreme suggestion very attractive either, namely, rising consumption can always compensate future generations for a deterioration in environmental conditions. There is the danger, however, that preferences will accommodate to a changing world. Individuals born into a world where, for example, 90 per cent of all species are lost might build up preferences such that they do not feel this as a great loss so long as their food resources and consumption possibilities are not significantly affected. Arguably, many people living in urban areas have already become used to encountering only a small number of animals and plants personally. The same holds potentially true for environmental pollution as well. Still more frightening is the emerging possibility of adapting individuals to a world empty of renewable resources and environmental amenities and full of pollution via genetic engineering. The point is that preferences are determined partly by the changing outside world.[17]

However, proponents of WS sincerely believe that in the end economic growth will be rather beneficial and not harmful to the environment, an argument which, to be fair, they have put forward from very early on (see, for example, Beckerman 1974; World Bank 1992). The paradigm of WS would therefore not have to rely upon the highly questionable substitutability assumption with respect to natural capital as a more direct provider of utility.

I shall therefore take the conjecture that economic growth will improve the environment as the main proposition of WS with respect to environmental degradation and call it 'environmental optimism'. As we will see, proponents of SS tend to argue the opposite, namely, economic growth will degrade the environment, a proposition I will call 'environmental pessimism'. It is therefore necessary now to analyse the link between economic growth and environmental degradation.

3.3.2 Economic Growth and the Environment

Before discussing in detail the theoretical arguments concerning the environmental consequences of economic growth and the available evidence which will fill the rest of this section, let us examine first why it is that economic activity, and especially economic growth, pose a problem for the environment. The first law of thermodynamics, that is, the law of conservation of mass, implies that no material can be destroyed; it can only be transformed into other goods (bound to become waste at some time), and into waste, pollution, and so on; in other words, if all other things are equal, then economic activity, and the more so economic growth 'is inevitably an entropic process that increases the amount of unavailable (that is, dissipated or high entropy) resources at the expense of available (that is, ordered or low entropy) resources: the stock of wastes increases and environmental quality decreases' (Smulders 1995, p. 165).[18]

Of course, it is the WS proponents' argument that all other things are *not* equal, and I start by presenting the case for environmental optimism. After that, the opposite case of environmental pessimism is put forward, and I assess whether empirical evidence can decide between the opposite claims.

3.3.2.1 The theoretical case for environmental optimism

There are several theoretical reasons suggesting that economic growth might be beneficial for the environment despite the first law of thermodynamics:

1. One that is often cited (for example, by Beckerman 1992a, 1992b; Baldwin 1995; Martini and Tiezzi 2014; Tyllianakis and Skuras 2016; Dupoux and Martinet 2022) is that environmental quality is a normal, possibly even a luxury, good, as economists call it; that is, a good with an income elasticity greater than zero, possibly even greater than 1. As incomes grow, environmental concern and with it demand for environmental improvements rise (normal good) or rise more than proportionally (luxury good). Environmental protection then rises if the political system is responsive to the preferences of its people. If past environmental destruction is not infinitely persistent and irreversible, the rising share of environmental protection in relation to total expenditure implies that environmental quality increases.

   A similar argument is that with rising incomes, people become better educated and better able to express their desires and defend their interests. It becomes more difficult with rising incomes to externalise environmental costs upon others, because the latter are better able to fight this degradation of their welfare. Also, richer people are more likely to be aware of environmental hazards due to better education and information. Hence, in rich countries more environmental costs are internalised than in poor countries, implying that pollution in poor countries is higher.
2. The second reason buttresses the first one in that it suggests that rich countries not only have higher demand for environmental protection, but also have better means for satisfying this higher demand. Rich countries can better afford spending money on the environment and have the technical equipment for environmental protection. But it is more than that: rich countries also 'have the advanced social, legal and fiscal infrastructures that are essential to enforcing environmental regulations and promoting "green awareness"' (Baldwin 1995, p. 61).

3. The third reason is that with economic growth, it becomes more likely that more modern and less pollution-intensive man-made capital is newly installed or replaces old capital.
4. The fourth reason is that at higher levels of income, the share of relatively more pollution-intensive industries (manufacturing sector) goes down while the share of relatively less pollution-intensive services sector goes up.
5. The fifth reason puts forward a similar, more fundamental argument: economic growth is not logically equivalent to rising output in physical terms but to rising output in value terms (Pezzey 1992a, p. 324). That is, economic growth means a rise in the total net value of economic output. Resource depletion and environmental destruction as such are not objectives of economic activity; rather, they are 'unwanted' side-products of adding value to the inputs of production. Where this value comes from and how pollution-intensive it is are logically separate questions from the growth in value. The economic value per unit of pollution can rise or, inversely, the pollution intensity per unit of economic value can fall.

   The same argument applies to resource use and resource intensity which would further buttress the optimists' view on resource availability in Section 3.2, p. 54. Note that this decoupling of economic value from resource input and pollution can stem either from technical improvements or from the changing pattern of output away from resource- and pollution-intensive goods and services towards goods and services that are less intensive in resource use and pollution. It can also stem from the reuse of goods, recovery, and recycling of materials. There is 'no definite upper limit' on the 'service output of a given material' (Ayres 1997, p. 286).
6. The sixth reason takes a closer look at the environmental consequences of poverty. Poor people are often locked into a trap in which poverty causes environmental degradation, which causes poverty in return. Poor people are driven to exploit their environment out of sheer lack of alternatives, which in turn makes them poorer, which in turn raises the pressure on the environment, and so on (Barbier and Hochard 2019). As Markandya and Pearce (1988, p. 35) observe, the very high time preference rates of poor people, which is due to their poverty, make it completely rational for them to destroy the resources their living is dependent upon. Deforestation for the collection of fuelwood seems a good example of this conjecture. Beckerman (1992a, p. 482) concludes that 'in the end the best – and probably the only – way to attain a decent environment in most countries is to become rich'.
7. A seventh reason is that, with rising incomes, the pressure on the environment due to population growth decreases, since population growth tends to decline or even turns into population shrinkage. All other things being

equal, more people means more pollution (Cole and Neumayer 2004). Figure 3.6 plots the average fertility rate (average number of births per woman) in 2022 for almost all countries in the world against the natural log of their average 2022 per capita income in US$ converted at purchasing power parity. The fertility rate is a better indication of the effect of per capita income than population growth rates, which are subject to distortion by immigration. There is a clear tendency for lower fertility rates to be correlated with higher per capita incomes, as shown by the trend line. Note that quite a few countries are now well below the replacement rate of 2.1 children per woman, meaning that their populations are likely to shrink in the future unless counterbalanced by immigration.

3.3.2.2 The theoretical case for environmental pessimism

There are several objections to the proposition that economic growth is beneficial to the environment, however.

1. The first objects to the presumption that the rich care more about the environment than the poor do (see, for example, Martinez-Alier 1995, 2002; 2023; Roy and Hanaček 2023). A similar argument is that although environmental concern might rise with income and perhaps even more than proportionally so, rising incomes also lead to an inflation in demand for all kinds of things. More and more goods and services and more and more new goods and services need to be produced to satisfy the rich consumer's desire, which means higher pressure on the environment. Poor people do not travel by airplane very much and do not drive Porsches.
2. The second objection is that while pollution per unit of output might decrease, total pollution might still increase if the rate of growth in output is higher than the rate of decrease in pollution per unit of output. As Lopez (1992, p. 154) observes for technical change, its effect on pollution is in principle ambiguous:

   > Technical change has two effects: (i) it increases the efficiency of conventional factors of production, and (ii) it may generate biases toward more or toward less environment-intensive technologies. Insofar as (i) is effectively equivalent to conventional factor accumulation, its effect on the environment is negative. The effect of (ii) is to decrease environmental degradation if technical change is environment saving. Given that environmental control costs are a very small fraction of the total cost in developed countries, it is likely that the bulk of the R&D efforts by the private sector are still oriented more toward the development of conventional factors saving techniques rather than to environmental saving techniques. Hence, it is likely that the effect (i) of technical change dominates the effect (ii), implying that growth, even if generated by technical change only, will lead to increased pollution.

On the other hand, Cavendish and Anderson (1994, p. 774) cite evidence that 'in a large number of cases pollution per unit of output can be, and often historically has been, reduced by factors of 10, 100, and sometimes 1000 or more (depending on the case) once the process of substitution is complete'. But there are also limits to this trend of substitution – first, physical limits, but second, and much more important, economic limits, because often the marginal costs of reducing pollution per unit of output rise steeply as pollution tends towards zero. Not everything that is physically possible in theory will ever be put into practice because doing so would be prohibitively costly.

3. A third objection is that in so far as pollution is decreasing because the pattern of output is changing, there are limits to this as well. This time, however, the limits are not determined by technology or economic cost, but rather by people's preferences. While it might be possible to substitute recreational and cultural activities, which tend to have rather low pollution intensity, for the consumption of material goods that are more polluting in production, this substitution cannot go on indefinitely. As far as one can judge from people's revealed preferences, material goods are rather highly appreciated.
4. The fourth objection acknowledges that structural changes in the economy impact environmental quality. This does not work unambiguously in favour of the environment, however. At low levels of per capita income, with rising incomes, the share of agriculture, forestry, and mining (the primary sector) goes down while the share of industry and manufacturing (the secondary sector) goes up, with possibly detrimental effects on the environment, especially if not accompanied by tighter environmental policies. Also, at low levels, the share of heavy polluting manufacturing (such as chemicals, steel, cement production, and heavy engineering) usually increases with economic growth. The environmental impact of structural change thus very much depends on where a country is in the process of structural change. Moreover, simply because the share of the manufacturing sector goes down does not imply that the absolute size of a country's manufacturing sector shrinks. A smaller percentage of a much bigger pie still makes for a larger piece of cake.
5. The fifth objection suspects that one important reason why high-income countries could become cleaner was that they exported their most-polluting industries to lower-income countries. By importing goods that are highly resource- or pollution-intensive but produced elsewhere, developed countries can make their environmental record look cleaner than it actually is if one took account of the international trade linkages and attributed resource use and environmental pollution to the final consuming country. Of course, when everybody wants to become rich, there eventually will be

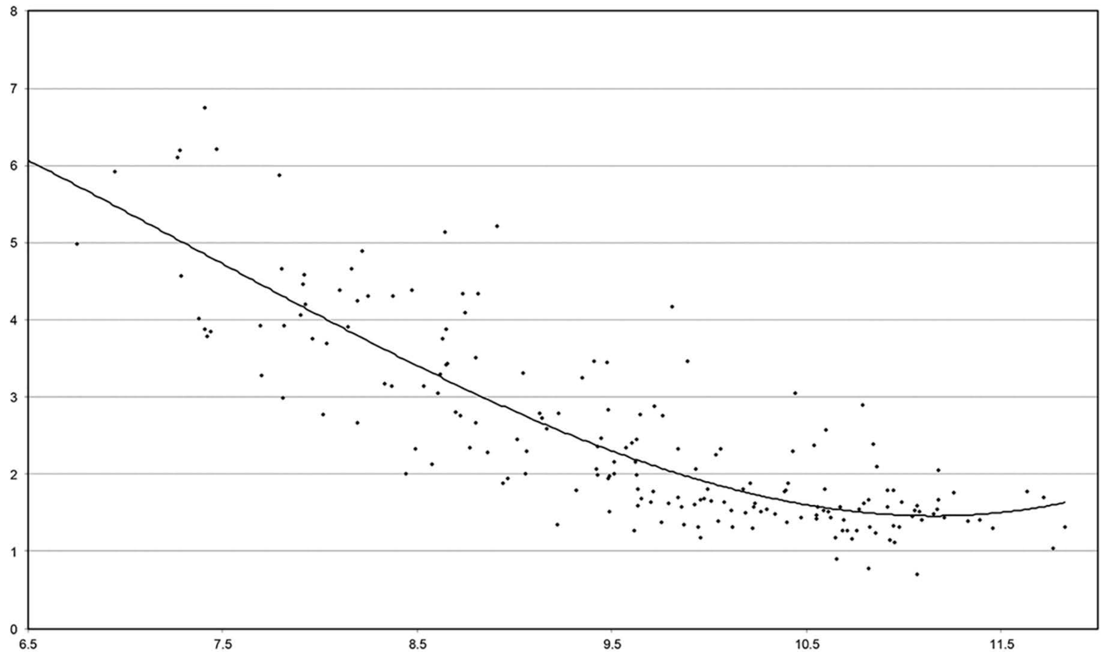
no poor country 'pollution havens' to take on the dirty industries. Hence, becoming 'cleaner' as a consequence of becoming rich will no longer be possible. Cole and Neumayer (2005) find evidence that developed countries have increasingly satisfied their demand for pollution-intensive output by imports. For a review of the literature and further evidence on the pollution haven hypothesis, see Copeland et al. (2021) and Bashir (2022).

6. The sixth objection contests that economic growth is a necessary and sufficient condition for reducing population growth.[19] Instead, investing in female education and providing retirement pension schemes are the best ways to reduce population growth. While these might often correlate with per capita income, economic growth is neither necessary nor sufficient to achieve the goal: there are rich countries like Saudi Arabia with a per capita income in purchasing power parity of US$51,246 in 2022 and a relatively high fertility rate of about 2.4 births per woman, whereas Nepal, with a much lower per capita income of only US$4632, has a lower fertility rate of about 2 births per woman (data from World Bank 2024). Quite clearly, fertility rates and, consequently, population growth are determined by many other factors besides the level of a country's income: while there is a trend detectable in Figure 3.6, there is also considerable variance around the trend. Having said that, the link between per capita income and fertility rates is fairly consistent and strong, as Figure 3.6 attests to.

3.3.2.3 Empirical evidence

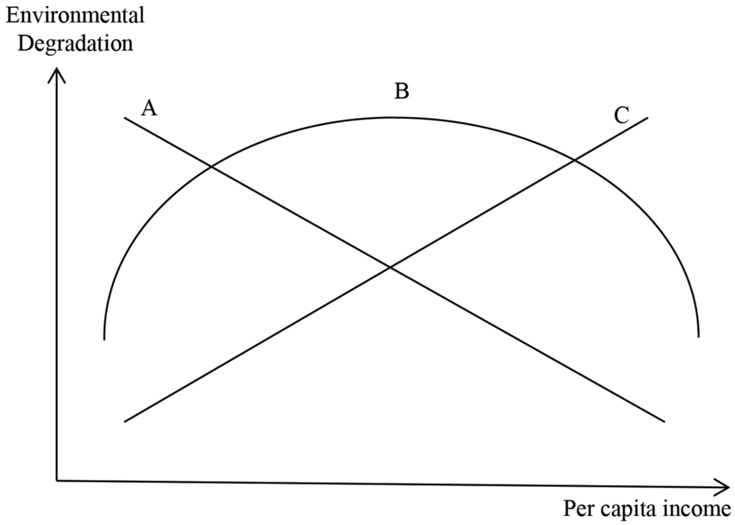
From theory, no definite answer can be found. Economic growth could be either good or bad for the environment. Quite clearly, the environmental consequences of economic growth are an empirical rather than a theoretical matter. What does the evidence say? Available econometric studies, some time series, but mostly cross-sectional or time-series cross-sectional, paint a complex picture depending on which indicator for which aspect of environmental quality one chooses to focus on. The empirical literature on the link between economic growth and the environment has literally exploded since the pioneering studies of Shafik and Bandyopadhyay (1992), Grossman and Krueger (1993, 1995), and Grossman (1995), to mention just a few. Sarkodie and Strezov (2019), Pincheira and Zuniga (2021), and Leal and Marques (2022) review this vast literature. By contrast to these three review studies, which are quite comprehensive in the number of studies reviewed, Stern (2017) and Cherniwchan and Taylor (2022) are much more selective in the empirical studies they review, but their reviews are also considerably more analytical as well and therefore highly recommended to interested readers.

One has to be rather cautious in interpreting the generated results by empirical studies: first, the studies need to rely on often poor-quality data on



Note: Fertility rate vertical scale, log of income horizontal scale.
Source: World Bank (2024).

Figure 3.6 Fertility rates and per capita income in 2022



Source: Author.

Figure 3.7 Environmental degradation and per capita income

environmental pollution, and many aspects of environmental degradation cannot be studied in a cross-national time-series context because data are lacking altogether; second, critics have argued that most of the empirical results have been generated with inappropriate or highly problematic econometric methods (Stern and Common 2001; Stern 2004; Wagner 2008; Galeotti et al. 2009; Stern 2010, 2017); and, third, different studies have come up with different relationships for the same indicator depending on the modelling technique or sample studied. If, despite these caveats, one takes the studies at face value, then one can distinguish three ideal-type results (see the stylised graphs in Figure 3.7):

1. Indicators showing an unambiguous improvement as incomes rise. This is a rare finding. Examples would be access to clean water and adequate sanitation (stylised graph A).
2. Indicators showing a deterioration first until a certain level of income is reached, after which an improvement takes place. That is, on a graph with environmental quality on the ordinate and income on the abscissa, the graph would show a U-curve. Often in the literature, however, the level of pollution is put on the ordinate so that the graph shows an inverted U-curve

(stylised graph B). This curve is called an 'Environmental Kuznets Curve' (EKC), an environmental variant of the much older Kuznets curve named after Kuznets (1955), who hypothesised that income distribution would first become more unequal as economic growth started off in a country and more equal later on. This has been the most typical finding in the empirical literature. Examples of the EKC would be the emission of suspended particulate matter, sulphur oxides, nitrogen oxides, carbon monoxide, volatile organic compounds, faecal coliforms, the quality of ambient air, and the rate of (tropical) deforestation. This second case has gained the most attention, for reasons I shall discuss later.

3. Indicators showing an unambiguous deterioration in specific aspects of environmental quality as incomes rise (stylised graph C). Examples would be the generation of municipal waste and the emission of CO_2 per capita, though note that many high-income countries of the 'Global North' are trying to reduce their CO_2 and other greenhouse gas emissions now, despite continued economic growth.

It follows that one must look carefully at specific environmental indicators to gauge the environmental consequences of economic growth. Put differently, *the* effect of economic growth on the environment does not exist in a vacuum.

Are environmental improvements policy induced?

Unfortunately, the reduced-form econometric models that are commonly used in the EKC literature are not able to discriminate between the varying theoretical hypotheses discussed previously to explain the observed data. It is, for example, not possible to tell clearly which part of the effect comes about via quasi-automatic changes during the course of economic growth (for example, by substituting cleaner technologies for dirtier ones or by a change in the structure of the economy) or comes about via deliberate environmental policy efforts (Grossman and Krueger 1995, p. 372).

Much of the literature, going back to Grossman and Krueger's (1993) truly seminal study, distinguishes between three separable effects: a scale effect, a composition effect, and a technique effect. At the risk of simplification, the scale effect suggests that economic growth, all other things being equal, results in more environmental pollution as increases in economic output generate more pollution, practically on a one-for-one or proportional basis if nothing else changes: double economic activity, double pollution levels. What change, however, are the composition and the technique effects.

The composition effect refers to the compositional structure of the economy and how this structure changes with economic growth. The economies of very poor countries tend to be predominantly agrarian (the so-called primary sector: agriculture and forestry but also, if the country has such resources, mining and fossil fuel extraction, which is far less environmentally benign than agriculture). As economies grow, there is a compositional change towards more energy- and pollution-intensive industries which manufacture goods, and this so-called secondary sector becomes increasingly important as a share of the overall economy. However, as countries grow yet further, the tertiary sector consisting of services that, relatively speaking, tend to be less pollution-intensive than industrial manufacturing becomes the dominant sector in the economy and the secondary sector share of the economy shrinks again. The composition effect, again all other things equal, is environmentally detrimental for relatively poor countries that grow into becoming major manufacturing powerhouses. China's experience over the last two to three decades immediately springs to mind. The composition effect is environmentally beneficial, however, for what some call post-industrial countries like much of Western Europe, North America, and other OECD countries whose high per capita income economies are already dominated by the services sector, and the industrial share of their economies has considerably shrunk from its heyday.

The technique effect refers to reductions in pollution intensity, that is, in pollution per unit of economic output. As the name suggests, this may come about via technological progress. However, the question is what drives this technological progress. Does it come about quasi-automatically as a by-product of economic growth, or is it policy induced and thus driven by increasingly stringent environmental regulation policies that incentivise economic actors to search for and bring about environmentally benign technology innovation? The technique effect can thus also capture the effect of environmental policies.

Before we explore further what drives the technique effect, let us first address how the scale, composition, and technique effects together fit with the three stylised graphs of Figure 3.7. For the empirically rare relationship A, the scale effect needs to be non-existent or negligibly small, and the technique effect needs to be large and consistent to monotonously bring down pollution levels with every increase in per capita income. For the stylised relationship C, the scale effect needs to be very strong and overwhelm any beneficial effect on the environment that may come from the composition effect at higher levels of per capita income, and the technique effect needs to be small or non-existent. For the most commonly found stylised relationship B, at low levels of per capita income, the scale effect and environmentally detrimental composition effects are dominant. After the hump of the EKC, that is, the inverted U-curve, either the technique effect dominates the scale effect as well as any still occurring environmentally detrimental composition effect, or the composition effect has already turned environmentally positive, and together with the technique effect, they dominate the scale effect such that environmental pollution goes down with further increases in per capita income.

As one can see from the above, the technique effect is ultimately what is needed for economic growth to be good for the environment, for pollution levels to go down with further increases in per capita income, and the more important it is that we return to the question of what drives the technique effect. Grossman and Krueger (1996, p. 120), two pioneers of the EKC, already suggested that environmental policies, driven by vigilance and advocacy, play an important role in shaping the observed relationship between economic growth and environmental pollution. This early suggestion has been corroborated by a body of subsequent empirical studies. Selden et al. (1999), for example, have decomposed changes in US emissions of particulate matter, SO_x, NO_x, non-methane volatile organic compounds, carbon monoxide, and lead over the time period 1970 to 1990 into a scale, composition of the economy, and various technique effects. They found that the non-energy efficiency technique effect had the largest impact on the reduction of these emissions over time, both absolutely and per capita. What this finding tentatively suggests is that governmental regulation of emissions, that is, an induced policy response to growing environmental pollution, and emission abatement technology played a significant role in bringing about these improvements in environmental quality (p. 28). More recent studies from different time periods, looking at different pollutants and different locations all point in the same direction – see, for example, Levinson (2009, 2015), Grether et al. (2009), Brunel (2017), Shapiro and Walker (2018), and Cole and Zhang (2019).

While all studies seem to agree on the overall dominant importance of the technique effect, not all studies agree that the dominant driver behind the technique effect is environmental policy. Najjar and Cherniwchan (2021) find that only less than 40 per cent of particulate matter emission reductions in Canada can be attributed to regulation. Similarly, reductions of carbon and other greenhouse gas emissions during time periods without any major regulation of such emissions are hard to square with policy being the predominant driver behind the technique effect (Cherniwchan and Taylor 2022). Nevertheless, most evidence suggests that the technique effect is largely or even predominantly driven by more stringent environmental policies.

The role of governance, inequality, and civil society

If all evidence suggests that the technique effect is the dominant driver behind environmental pollution reductions and most evidence suggests that environmental policy is the dominant driver behind the technique effect, then the next question is what is the dominant driver behind environmental policy? Scholars have explored how governance in general, and democratic political regime type in particular, economic and educational inequality, as well as the strength of environmental civil society, may impact the likelihood that a country adopts stringent environmental policies.

There are many reasons why one would expect democracy to have a positive effect on the environment (Payne 1995; Neumayer 2002a): in democracies citizens are better informed about environmental problems (freedom of the press) and can better express their environmental concerns and demands (freedom of speech), which will facilitate the organisation of environmental interests (freedom of association), which will, in turn, put pressure on politicians operating in a competitive political system to respond positively to these demands (freedom to vote), both domestically and via international cooperation. In non-democratic countries, on the other hand, governments are likely to restrict access of their population to information, restrict the voicing of concerns and demands, restrict the organisation of environmental civil society groups, and isolate themselves from citizens' preferences. In other words, in democracies, if citizens are concerned about environmental problems, this will eventually require policymakers to exhibit stronger environmental action to address these concerns and satisfy the demand for environmental protection measures.

Moreover, the small ruling elite in autocracies is likely to control the highly polluting industries as well, thus disproportionately benefiting from externalising environmental costs. This elite has little interest in environmental pollution control, not least because the accumulated wealth that comes with political control allows them to buy private environmental amenities (for example, residential properties far away from the sources of pollution), such that they do not fall victim to the degradation of public environmental amenities that is the consequence of their own environmental cost externalising.

A positive association between democratic regime type and environmental quality has been suggested by many studies (Barrett and Graddy 2000; Farzin and Bond 2006; Li and Reuveny 2006; Bernauer and Koubi 2009; Kim et al. 2019; Mavisakalyan et al. 2023). Consistent with such a positive correlation between democracy and environmental outcomes, Neumayer (2002a) and Neumayer et al. (2002) find evidence that democratic countries exhibit stronger environmental commitment, while Neumayer (2002b) provides less robust evidence for a positive link between trade openness and environmental commitment. For example, more democratic countries are more likely to sign and ratify multilateral agreements, they are more likely to have a National Council for Sustainable Development and set a larger percentage of their land area under protection status. Bättig and Bernauer (2009) show that while democracies do not necessarily outperform autocracies in terms of greenhouse gas emission reductions, they are more cooperative in terms of politically and legally committing to climate change policies.

Democracies provide equal rights to all citizens, but this does not translate into equal influence on public decision-making. Inequality in incomes and education levels will systematically bias decisions against environmental protection (Boyce 1994, 2002, 2008, 2018, 2023). The benefits from environmental pollution tend to be concentrated towards the upper end of the income distribution, as relatively well-off company owners and shareholders benefit from higher profits following environmental cost externalization and high-consumption richer individuals benefit from higher consumer surplus. In contrast, the costs of environmental pollution tend to be concentrated towards the lower end of the income distribution, as poor people often do not have the resources to shield themselves against environmental pollution by buying private environmental amenities, as the relatively rich can do. Increased economic inequality will therefore lower aggregate willingness-to-pay for environmental policies, unless the income elasticity of demand for environmental protection – typically presumed to be positive, possibly even above one – is so strong as to outweigh the ‘price effect’ arising from foregone extra profits and consumer surplus from environmental cost externalization (Scruggs 1998; Boyce 2002). The latter is unlikely, however, given that relatively wealthy individuals benefiting from such cost externalization can substitute private environmental amenities for public ones or can spatially distance themselves from pollution hotspots by buying residential property in relatively unaffected areas. For example, in São Paulo it is a common phenomenon for very rich people to live well outside the megalopolis with its polluted air and congested streets and to fly into the city for work and leisure purposes with private or chartered helicopters. Finally, in as much as concentrated economic power also allows a greater influence on political decision-making, greater inequality will also bias political decision-making against environmental protection. Thus, differences in ability-to-pay buy differences in political power to influence decisions. For empirical studies on the effect of inequality on environmental outcomes, see, for example, Torras and Boyce (1998), Boyce et al. (1999), Magnani (2000), Holland et al. (2009), Vornovytskyy and Boyce (2010) and Bez et al. (2024).

Governance is of course about much more than democracy. Dasgupta et al. (2006) analyse the effect of a World Bank measure of a country’s policies and institutional capacity for environmental governance on air pollution levels. This measure is correlated with democracy, but far from perfectly. Finding that environmental governance matters, they conclude from their results that ‘policy reform alone is sufficient to reduce air pollution significantly, even in overcrowded, geographically vulnerable cities in countries with very low incomes’ (p. 1609). Shapiro (2023) proposes and provides some corroborating evidence that countries with strong financial, judicial, and labour market institutions experience higher environmental quality because they are better able to attract relatively clean industries as these institutions provide them with a comparative advantage over other countries.

As regards the role of civil society, in particular, environmental non-governmental organisations (ENGOs), Cropper et al. (1992) suggest that ENGO lobbying had a significant effect on the probability that the US Environmental

Protection Agency (EPA) cancelled a harmful pesticide registration. Riddel (2003) focuses on a different aspect of ENGOs' influence in analysing their role in election outcomes and finds that the Sierra Club and the League of Conservation Voters had a significant effect on US Senate election outcomes by leveraging campaign contributions channelled through political action committees. Carter (2007, p. 144) concludes from his reading of the available evidence: 'There is little doubt that environmental groups have been the most effective movement for progressive environmental change.' Two quantitative cross-national studies support this conclusion. Fredriksson et al. (2005) find that the number of environmental advocacy groups in a country has a statistically significant negative effect on lead content levels in gasoline, while Binder and Neumayer (2005) estimate the effect of environmental pressure group strength on air pollution levels and conclude that such strength exerts a statistically significant impact on sulphur dioxide, smoke, and heavy particulate concentration levels. Koubi et al. (2020) find that when international environmental treaty provisions allow greater participation by civil society groups, this increases the likelihood of treaty ratification. Going beyond ratification, Böhmelt and Betzold's (2013) study suggests that a higher level of state commitment follows greater participation by ENGOs in international environmental treaty negotiations. A few studies have also analysed the effects of party strength. Both Neumayer (2003a) and Bernauer and Koubi (2009) find that countries with stronger green parties have lower air pollution levels.

Unpleasant implications of EKC findings

An important caveat to keep in mind when interpreting the evidence and especially concerning those indicators which appear to follow an EKC is that most less developed countries (LDCs) are just about to enter the level of income where many emissions are still rising and doing so rapidly. The turning point after which pressure on the environment is supposed to diminish varies widely depending on the pollutant looked at as well as the estimation technique and sample used. Cole and Neumayer (2005) examine many EKC studies and estimate when pollution levels are predicted to fall in developing countries, based on a number of economic growth scenarios. Although the estimated EKCs may be overly optimistic, they find that the implications of the EKC for developing countries are still rather bleak: for many pollutants, emissions are predicted to increase for most of the developing countries for many years to come, even in an optimistic high-growth scenario. These projections thus open the alarming possibility of *total* pollution rising tremendously with future economic growth. As Ekins (1997, p. 824) has put it, the existing evidence shows 'a stark environmental prospect, unless past growth/environment relationships can be substantially changed'.

Another problem is that practically all studies look at either emission intensity, that is, emissions divided by GDP, or emissions per capita. As concerns the latter, with continued population growth, falling emissions per capita need not translate into falling total emissions. It took only 12 years for the world population to grow from 7 billion to 8 billion people in 2023, and it is likely to peak somewhere around 10.3 billion people according to the 2024 revision to the World Population Prospects projections of the UN Population Division.[20] For Baldwin (1995, p. 61), 'the nightmare scenario is that income growth in the poorest LDCs would stall at the point where they are in the high-emission stage, but not quite out of high-growth stage of their demographic transition'. Or even if income growth does not stall and population growth rates fall further or indeed absolute population size starts shrinking, it might be too late since environmental thresholds might have been exceeded, and dramatic and possibly irreversible environmental deterioration will already have taken place. As Panayotou (1993, p. 1) observes, these thresholds are more likely to be relevant in today's low-income fast-growing countries where often 'tropical resources such as forests, fisheries and soils' exist which 'are known to be more fragile and less resilient than temperate resources'. The problem is that nobody knows where those thresholds are and attempts to measure them must rely on very crude assumptions that can easily be contested by opponents.

One cannot even rely on total pollution decreasing again once high enough levels of income are reached, since econometric evidence does not provide stable causal relationships but rather associations or correlations at a particular moment in time. There is absolutely no guarantee that the environmental quality of a country that is *now* poor will be equal to the environmental quality of a country that is *now* rich *once* it has become rich itself. This is because external and internal conditions in low-income countries can be quite different from the external and internal conditions of countries with high incomes now at the time of their own development.

3.4 CONCLUSION

Chapter 3 has assessed the validity of the opposing claims of WS and SS with respect to the substitutability of natural capital. The conclusion that arises from the analysis is that both paradigms rest on certain assumptions as well as hypotheses and claims about the (distant) future that are non-falsifiable. That does not mean, of course, that either paradigm is nonsensical. Both have some theoretical plausibility as well as some empirical evidence in their support.

To see this tension between, on the one hand, the paradigms having some theoretical and empirical plausibility and, on the other, both paradigms resting on non-falsifiable assumptions and hypotheses, take the four propositions from resource optimism as an example. The power of resource optimism stems from the fact that not all four propositions need to hold true in isolation, but that any one of them or some combination of them is sufficient to save the economy from running out of resources. Resource optimism is grounded in the belief that any natural resource can be substituted by another resource, *or* by man-made capital, *or* by technical progress, *or* by some combination thereof. The critical assessment of resource optimism in Section 3.2, p. 54 sheds some doubt on all four propositions when examining them in isolation. But none of the propositions could actually be refuted, and even less so if they are seen together and their interactions are taken into account.

On the other hand, it was also shown that none of the propositions can necessarily be relied upon either. Each one of them ultimately rests on basic beliefs about future substitution possibilities or technical progress. As Lecomber (1975, p. 42) wrote as long ago as 1975:

> Everything hinges on the rate of technical progress and possibilities of substitution. This is perhaps the main issue that separates resource optimists and resource pessimists. The optimist believes in the power of human inventiveness to solve whatever problems are thrown in its way, as apparently it has done in the past. The pessimist questions the success of these past technical solutions and fears that future problems may be more intractable.

What makes the resource optimism of WS non-refutable is that the optimism is only sound if *at any point of time in the future* at least one of the propositions will hold. The propositions of WS are surely logically conceivable, but whether they are possible in practice or even likely to occur, we do not know. The only thing we do know is that they are *not* certain. As Gerlagh and van der Zwaan (2002) and Cohen et al. (2019) point out, substitutability in the long run might be very limited, even though there can be very good substitution possibilities in the present and near future. Watkins (2006, p. 513) is similarly cautious in concluding his otherwise optimistic assessment of resource availability: ‘Will supply always be plentiful? That is more than anyone could pretend to know. … This degree of uncertainty encourages agnosticism about whether technology and new knowledge will continue to keep the forces of depletion at bay.’

The contest between WS and SS cannot be settled by theoretical inquiry. Nor can it be settled by empirical inquiry since such an inquiry would be dependent on information that is only ‘forthcoming in the always receding future’, where ‘predictions … are clouded by uncertainty regarding preferences, human ingenuity and existing resource availability’ (Castle 1997, p. 305). As the analysis in this chapter has shown, there has been rather limited actual empirical research on the question of substitutability. But it would be a mistake to believe that more research could solve the dispute between WS and SS. For as Victor et al. (1995, p. 83) observe:

> the question of sustainability is not really one of short term substitution … based on currently available technologies. Rather it is the potential for new, yet to be invented, technologies to substitute for natural capital. No one can reliably predict what new technologies will be developed, and whether the assumed degree of substitution implicit in weak sustainability will become reality.

This conclusion differs starkly from the apparent self-confidence with which proponents of both paradigms of sustainability advance their position and presume that their assumptions hold in reality. We actually know much less about the substitutability of natural capital in the production of consumption goods and services than the two paradigms of sustainability would have us believe.

What is true for resource availability or the 'source' side of the economy applies to the 'sink' side of the economy as well. Whether natural capital should be regarded as substitutable in the utility function is in principle a matter of speculation as we do not know the preferences of future generations. In so far as future preferences are endogenous and contingent on past levels of environmental degradation, the substitutability hypothesis might be a self-fulfilling prophecy. I also argued that inferring information from the preferences of the current generation does not provide an unambiguous picture either. The available evidence that supposedly shows that a substantial minority of individuals exhibit something close to lexicographic preferences with respect to natural capital is rather shaky. Also, the majority of individuals seem to exhibit preferences that are compatible with the substitutability assumption. It must be said, however, that proponents of SS see the non-substitutability of natural capital as a direct provider of utility more normatively than positively, what human beings should want rather than what their actual preferences reveal. They frame the issue as one of an inviolable right of future generations to be free from long-term environmental degradation. As a normative position, it is non-refutable, however.

The next subsection in this chapter looked at the link between economic growth and the environment. This is because proponents of WS sincerely believe that, in the long run, the state of the environment improves with economic growth, so that they can rely less on the controversial assumption that natural capital is substitutable in utility functions as well. The results found on resource optimism apply equally to the environmental optimism of WS. The proposition of WS that economic growth is good for the environment in the long run is logically conceivable, but we do not know whether it will be possible, let alone likely to occur. Only a few years after research on the EKC took off in the early 1990s, Ferguson et al. (1996, p. 28) argued that the existing evidence 'cannot be used to justify a view that economic growth … will automatically be good or bad for the environment. … The nature of this relationship lies, to a large extent, in the hands of those responsible for environmental policy and its enforcement.' As empirical evidence that has been produced since then, as reviewed in this chapter, has shown, this conclusion is as true now as it was 30 years ago: environmental improvements are driven first and foremost by policy choices. They are not the inevitable side or collateral benefit of economic growth.

There is nothing inevitable about environmental quality deteriorating at early stages of development. Panayotou's (1993, p. 14) claim that the existing evidence 'implies a certain inevitability of environmental degradation along a country's development path, especially during the take-off process of industrialization' is backed by much empirical evidence of the historical record so far and by and large rings true for what happened between 1993, when Panayotou made this claim, and the time of writing this fifth revision in 2024. But it need not hold going forward. Equally, Grossman's claim that 'attention to environmental issues is a luxury good poor countries cannot afford' (quoted in Ferguson et al. 1996, p. 6) does not logically follow from the existing evidence.

On the other hand, there is nothing inevitable about environmental quality improving at high levels of income either. This is because one cannot rely on economic growth curing environmental ills sooner or later. Following a development path along an environmental Kuznets curve might be far from optimal because of high environmental damage costs, because it might be extremely costly to raise environmental quality *ex post* (that is, after deterioration has taken place), because of the potential existence of environmental thresholds and irreversibilities, and because at least some forms of environmental degradation damage human health and economic productivity and are, ironically, themselves impediments to faster economic growth. Hence, there is a good case for policymakers to prevent environmental degradation at any stage of development.

One has to presume, therefore, that no general conclusions on the relationship between economic growth and the environment can be drawn. As Common (1995a, p. 103) has put it: 'Definitive "scientific" answers to these questions [of the relationship between economic growth and environmental quality] are impossible. They are essentially matters of informed judgement.' We simply do not know whether environmental optimism or pessimism is warranted. While there appear to be some cases historically where improvements in environmental quality coincided with higher incomes after some threshold of per capita income has been crossed, one cannot rely on economic growth curing environmental ills. Economic growth on its own does not seem to be a viable prescription for the solution of environmental problems. In the end, whether one thinks economic growth will be beneficial or harmful to the environment in the long run remains a matter of belief.

In the face of such uncertainty, I fully agree with van den Bergh (2011) that one should take an agnostic view towards economic growth and concentrate on environmental problems directly rather than focusing on 'degrowth', as advocated by Victor (2008), Jackson (2009), Hueting (2010), Kallis (2011), Kallis et al. (2020), Hickel (2021), and others. The battle to get strict environmental policies through the political process and then enforced is hard enough. The battle to persuade policymakers that their obsession with economic growth is misplaced and that less growth or even 'degrowth' is in the social interest is simply hopeless and a political non-starter. Moreover, it is not needed: environmental pollution is 'the enemy', not economic growth. Less economic growth may well be the consequence of strict environmental policies. But it would be a mistake to focus on economic growth to achieve environmental outcomes rather than to focus on environmental outcomes directly.

As Norton (1995, p. 125) observes, a paradigm that is accused of 'insufficient reach' can always answer 'by denying that some phenomena … are "real"' and argue that they are 'actually bogus entities that are the ontological fallout, the theoretical dross, of failed paradigms'. Norton (1995) argues that it is characteristic of extra-paradigmatic disagreements (as the one between WS and SS) that there is agreement neither on basic principles nor on the scope of the true subject matter of the discipline or a consensually accepted methodology. Hence, he concludes, these extra-paradigmatic disagreements are not amenable to confirmation or refutation. Also, he suggests, the basic principles of WS and SS are too abstract to be directly supportable, or refutable, by empirical evidence.

Norton's argument conforms with my own conclusion. However, my conclusion was derived from a rather different line of thought than Norton's. The main argument here is that even if there was agreement on the scope of the true subject matter and a consensually accepted methodology, it would still be impossible to confirm or disconfirm either paradigm. My argument thus provides an answer to the puzzling fact, observed by Tilton (1996, p. 92), that as concerns resource availability 'given the many opportunities participants have had to exchange ideas and views, one would expect to find some common core of accepted findings, some general consensus, emerging to which most if not all scholars subscribed'. But one does not find it. Tilton (1996, p. 92) rightly stresses how desirable a resolution of the conflict would be:

> [T]he competing paradigms not only promote contrasting outlooks on the future of humanity, they may influence that future to the extent their proponents are successful in promoting their particular policy prescriptions. This makes the continuing debate between the concerned and unconcerned troubling. The anticipated

> exploitation of exhaustible resources either does or does not pose a significant threat to sustainable development. Which it is, is important. The policy recommendations of one group cannot be right unless those of the other are wrong.

But if the analysis here is correct, then Tilton's (1996, p. 96) hope that the 'search for an appropriate and common paradigm' can be 'a first and essential step' to resolve the 'long-standing differences' between resource optimists and pessimists will not and, indeed, cannot, be fulfilled.

One problem with the two paradigms of sustainability is that they are quite general in their claims about substitutability of natural capital and allow little distinction for specific cases. They put their arguments forward as generally applicable, apodictic, obvious a priori truths rather than as specifically applicable and empirically contingent claims. Pearce (1997, p. 296) is right in saying that it is incorrect 'to caricature the issue as one of total substitutability' versus total non-substitutability.

As I argued in this chapter, the *likelihood* that natural capital is either abundant or can be substituted by other forms of capital crucially depends on which form of natural capital one is looking at and cannot be answered in general terms. I argued that abundance and substitutability are much more plausible conjectures for the part of natural capital that provides natural resource input into the production of goods and services (the 'source' side of the economy) than for other functions of natural capital, particularly its pollution absorptive capacity (the 'sink' side of the economy) as well as its provision of environmental amenities. Put differently, WS has greater plausibility when it comes to the 'source' side of the economy and SS has greater plausibility for the 'sink' side of the economy.

In the next chapter, I explore this crucial issue further, taking into account the distinctive features of natural capital in a world of risk, uncertainty, and ignorance. I will argue that a *persuasive* case can be made that the preservation of some specific forms of natural capital is a necessary requirement for sustainability. This holds especially true for those forms of natural capital that provide basic life-support functions for humankind.

NOTES

1. For more details on this, see Barbier (1989, chapter 1).
2. However, the rise in oil prices was clearly linked to the exercise of market power by OPEC and not to dramatically rising natural resource scarcity, although there is some evidence that prices had started rising before 1973 (Slade 1982, p. 136).
3. Throughout the book, technical progress is to be interpreted broadly as encompassing everything from the *invention* of a new technique to *innovation*

and *diffusion*, that is, to the widespread incorporation of this technique into production processes.

4. Some natural resources are scarce in a physical sense. If they have no productive use, nobody cares about this scarcity, however. Scarcity in an economic sense I define as excess demand for the resource at a given price.
5. In a perfectly competitive economy, the interest rate is equal to the marginal product of man-made capital (Dasgupta and Heal 1979, p. 296).
6. It is a partial equilibrium model and is used here because it makes understanding the Hotelling rule easier than the formally better-suited, but less easy to understand, general equilibrium model that is presented in Appendix 2.
7. For a detailed discussion of the physical principles governing the possibilities of recycling material, see Georgescu-Roegen (1986), Biancardi et al. (1993, 1996), Khalil (1994), Kummel (1994), Mansson (1994), and Converse (1996).
8. An important assumption is that there is no depreciation of man-made capital. As Dasgupta and Heal (1979, p. 226) indicate, the basic results would go through as well with capital depreciation as long as capital depreciates at less than an exponential rate. Note also that technical progress, which Dasgupta and Heal exclude, could counteract exponential capital depreciation. On this, see the discussion of technical progress in Section 3.2.4, p. 72.
9. Note that it is bounded below by zero. With $\sigma = 0$, capital and resources are already perfect complements. A negative elasticity of substitution ($\sigma < 0$) is not possible. Formally, since both K and R are positive numbers and the absolute value of the MRS between K and R is always positive, σ can never be negative.
10. Slade (1987, p. 351) reports values that suggest that man-made capital's share and the resources' share are approximately equal. However, this is based on a misunderstanding. Berndt and Wood (1975), on which Slade based her values, included intermediate goods in the production function. Those intermediate goods do not fall from heaven, and presumably the share of man-made capital in those intermediate goods is higher than the share of resources, so that the ultimate share of man-made capital is still considerably higher than that of resources, thus reconciling the reported values with those of Solow (1974a), Hartwick (1977), and Dasgupta and Heal (1979).
11. Note that here labour is not assumed to be constant and therefore enters the production function explicitly.
12. This is the most commonly used measure for energy intensity. For other, more contested concepts of measuring energy efficiency, see Patterson (1996).
13. https://population.un.org/wpp/
14. https://data.worldbank.org/indicator/NY.GDP.MKTP.KD
15. This phenomenon was first described by Jevons (1865), which is why it is also called the 'Jevons paradox'.
16. Environmental degradation here means a decrease in the stock of (directly utility-relevant) renewable resources or an increase in the stock of pollution.

17. They are not as solid and unchanging as the Rocky Mountains, as Becker and Stigler (1977, p. 76) suggest.
18. Strictly speaking, and as mentioned earlier, this argument does not apply since the Earth absorbs a steady, constant energy influx from outside exceeding the current total world energy demand at about three orders of magnitude (Smil 2006). It does apply approximately, however, when most of this influx is – as at present – not used.
19. A more extreme position holds that people are the ‘ultimate resource’ (Simon 1996) and that population growth is not bad for the environment. This, however, is a minority position that is usually, but not always (see, for example, Boserup 1990), held by people who think that economic growth is the best way to protect the environment (see, for example, Simon 1990, 1996).
20. https://population.un.org/wpp/

4. Preserving natural capital in a world of risk, uncertainty, and ignorance

In the previous chapter, I argued that both paradigms are non-falsifiable, even though there is overwhelmingly strong evidence that non-renewable resources needed for the production of consumption goods and services are fairly abundant, as WS proponents would have it, whereas there is good evidence that at least certain forms of critical natural capital are not substitutable, consistent with the SS paradigm. But the question still open is this: If society is faced with risk, uncertainty, and ignorance about the consequences of running down natural capital, particularly renewable resources, which forms, how much, and at what cost should it preserve natural capital? This is the major topic of this chapter.

The first aim of this chapter is to indicate which forms of natural capital are more *likely* to be non-substitutable than others and are therefore in greater need of preservation. Note the emphasis on 'likely': from the analysis in Chapter 3, it follows that the best we can hope for is to make a *persuasive* case for the importance of the preservation of natural capital. The major objective of this chapter lies somewhere else, however. It tries to explore the difficulties in finding the extent to which these forms of capital need to be preserved and how much cost should be incurred for preservation.

Section 4.1 begins by highlighting distinctive features of some forms of natural capital. There are two aspects – basic life-support function and irreversibility of destruction – that distinguish some forms of natural capital from other forms of capital. The stratospheric ozone layer, the global climate, as well as biodiversity – broadly defined throughout this book to include genetic, species, and ecosystem diversity – all qualify but are not the only ones. Section 4.2 discusses in more depth what has hitherto been dealt with rather implicitly: that the real world is plagued by the absence of perfect information and certainty and characterised by risk, uncertainty, and ignorance instead.

Section 4.3 presents various approaches to coping with risk, uncertainty, and ignorance. The best-known ones are the precautionary principle, the concept of safe minimum standards (SMS), and the related concept of safe operating spaces within planetary boundaries. All three function as a kind of insurance policy against the uncertain, but potentially very large, costs of running down natural capital.

Section 4.4 discusses the difficulties that the existence of opportunity costs poses for policymakers adopting one of the approaches for dealing with risk, uncertainty, and ignorance. One option is to deliberately ignore opportunity costs. The other option is to seek preservation of critical forms of natural capital, subject to the constraint that the opportunity costs must not be ‘unacceptably high’. There are good reasons for both options, but the concluding Section 4.5 argues in favour of the second option and against ignoring opportunity costs. Such a position takes the sometimes awkward decisions and dilemmas policymakers face head-on rather than assuming them away. I argue that my position, which has been derived from the existence of distinctive features of natural capital in a world of risk, uncertainty, and ignorance and without any recourse to a rights-based theory, is, nevertheless, compatible with a moderate rights-based deontological position.

4.1 DISTINCTIVE FEATURES OF NATURAL CAPITAL

To establish a case for the explicit preservation of certain forms of natural capital, as SS proponents argue for, one must start by trying to show that there are some characteristics of these forms of natural capital that distinguish them from other forms of capital. In my view, there are two aspects that can justify such a distinction: the provision of basic life-support functions and irreversibility of destruction.

- Some forms of natural capital provide very basic and fundamental life-support functions that no other capital can provide, that is, functions that make human life on Earth possible (Barbier et al. 1994). Ecosystems and the biodiversity they contain are multifunctional in a way and to an extent that is not shared by other capital (Ehrlich and Ehrlich 1992; Swanson 1997; Barbier 2019; Dasgupta 2021; Giglio et al. 2024). They are the basis of all life, human and non-human: it is the world ecosystem that contains the economy, not the economy that contains the world ecosystem (Daly and Townsend 1993, p. 3). Humankind can exist, and indeed has existed in the past, without major man-made or other forms of capital, but it cannot live without functioning ecosystems. The most important value of natural capital is not that we can use fossil fuels, for example, but that nature enables the very existence of human life: providing food, water, fresh air, and a bearable climate. Ecosystems might be able to cope with piecemeal destruction for a long time, but if a threshold is exceeded, the whole system could break down. There are ‘limits to meta-resource depletion’ (Ehrlich

1989) and a human-caused mass extinction crisis could endanger the future of humankind (Dirzo et al. 2022).

- Other life-support resources that really are non-substitutable and whose destruction would often lead to catastrophes are the global climate and the ozone layer. These are fundamental life-support resources, the destruction of which would endanger the welfare of future generations. While the ozone layer is well on its way to recovery, the same cannot be said for the global climate. We continue to dump greenhouse gas emissions into the atmosphere far in excess of its natural regenerative capacity, despite the fact that climate change poses a formidable threat to sustainable development, as Section 2.4, p. 30 has shown. A very good argument can be made that precautionary action should be undertaken to prevent large and unpredictable changes in the global climate. Since we do not know exactly beyond which concentration of CO_2 and other greenhouse gases these changes will occur, we should make sure that our emissions stay well below the limit that the best available science suggests to be the critical level. This calls for drastic and immediate reductions in greenhouse gas emissions.
- A good case can also be made for not letting emissions, especially emissions of highly toxic and health-damaging pollutants, accumulate in the environment, as doing so would, again, endanger basic life-support functions. The aim should be not to let emissions exceed 'critical loads' after which the capacity of the receiving media to dissipate and diffuse emissions would be damaged. Not following this rule would mean that the stock of pollution is continuously rising over time, which is likely to endanger the sustainability goal.
- Some forms of natural capital are unique in that they cannot be rebuilt or recovered once they have been destroyed. That is, destruction of some forms of natural capital is irreversible or at least quasi-irreversible. Reversibility need not be technically or physically impossible. It is sufficient that reversing a destruction is theoretically possible but only at prohibitively high costs. In general, this is not the case for other forms of capital. Man-made capital can always be reconstructed if it has been destroyed. Reconstruction may take some time, but at least it is possible in principle and typically not prohibitively costly. Admittedly, this is not true for unique historical buildings which provide non-material value, but it is true for man-made capital used in production. Social capital destruction can also be hard to revert: social trust is hard to build up and easy to lose.
- Many features of climate change represent irreversible natural capital loss. The same holds for the destruction of biodiversity: for the time being at least, it is impossible to bring an extinct species back to life. At least so far. There are efforts to store the DNA of species threatened with extinction. One day, genetic engineering might bring 'extinct' species back to

life if their DNA has been stored beforehand, or maybe even from DNA that happens to have been perma-frozen in places of very high or very low altitude on Earth.

While these distinctive features might make a general case for the preservation of specific critical forms of natural capital, it does not give an answer to what extent and at what costs these forms of natural capital should be preserved. This is complicated by the widespread presence of uncertainty and ignorance, to which I turn now.

4.2 RISK, UNCERTAINTY, AND IGNORANCE

Given the distinctive features of natural capital, why can one not simply target all those forms of natural capital that provide basic life-support functions and would be irreversibly lost after destruction? If we lived in a world of certainty, there would not be any problem. But, unfortunately, there is widespread risk, uncertainty, and ignorance in the world we live in. Ignorance here means more than risk and more than uncertainty, two notions that are well known in economics.[1] I discuss all three in the order of descending closeness to certainty.

4.2.1 Risk

Risk refers to a situation where the set of all possible states of the world, the probability distribution over the set of possible states, and the resulting payoffs can be objectively known. Buying a lottery ticket is a good example of engaging in a 'risky' action because the odds of winning can be objectively known, as can the costs of buying the ticket and the value of potential prizes – hence, the expected gain or loss can be computed without any remaining doubt.

Unfortunately, typically, we are not confronted with a situation of risk in trying to judge the validity of running down natural capital because, in most cases, we do not know either the probability distribution of all possible states or the potential outcomes resulting from the different states of the world. Worse still, often we do not even know the complete set; that is, we are ignorant of the total number of possible states of the world.

Also, even a situation of risk poses fundamental problems for any attempt to ensure sustainability. Consider a situation in which there is a 99.9 per cent chance of winning a big gain but a 0.1 per cent probability of incurring a tremendous loss. Further assume that both gains and losses affect, at least partially, future generations as well. Should society engage in or refrain from this risky action? There is no obvious answer. A possible solution could be to refrain from any action that carries such risks since the present is committed to maintaining the capacity to provide non-declining utility into the future, and engaging in the action risks a tremendous loss and hence a decline in utility, even if the probability of this drastic loss is rather small. But is this solution plausible? Presumably not, because refraining from *any* action that risks a net loss brings with it an (opportunity) cost both to current and future generations. The fundamental problem is this: in a risky world, ensuring sustainability with certainty can – if at all possible – only be achieved at high costs, and if those costs are deemed too high to be acceptable, then sustainability can, at best, mean ensuring expected sustainability.

Economists would resort to inferring the risk preference or risk aversion of the present generation in order to compute the expected utility of the risky action. The decision criterion would be to engage in the action if the expected utility is positive and to refrain from the action if the expected utility is negative.

Of course, if there is a whole range of risky actions at a given time or over a bounded time interval, then, due to the law of large numbers, unlucky outcomes become compensated by lucky outcomes, and a net gain equal to the expected overall value of a whole set of risky actions results. But, things are different when potential losses, however unlikely, imply irreversible *and* catastrophic outcomes that cannot be compensated for. An obvious answer would be to refrain from actions that imply such outcomes, however unlikely they might be. But what to do if the outcomes themselves are not known with certainty? This already leaves the context of risk, so I move on to discuss uncertainty next.

4.2.2 Uncertainty

Uncertainty refers to a situation where the probability distribution over a set of possible states of the world and the resulting payoffs cannot be known objectively, but individuals have subjective beliefs about the distribution and the payoffs.[2] Those beliefs can be updated (and in many cases improved) over time.

Uncertainty comes rather close to our present state of knowledge about many rather novel and complex, but most pressing, environmental problems, such as climate change (Pindyck 2007; Heal and Milner 2018). We know many things about the effects of dumping greenhouse gases in the atmosphere, we know something about the likely average temperature rises and their climatic consequences, we can imagine different states of the world following, and we have some idea about the probability distribution over these different states of the world. Our knowledge about climate change is still rather poor, however, as the reports by the Intergovernmental Panel on Climate Change (IPCC) demonstrate (IPCC 2021, 2022a, 2022b).

The biological and socio-economic consequences of large-scale biodiversity loss are another good example 'for which our lack of knowledge is striking' (Heal and Milner 2018, p. 440). Biodiversity provides important economic values, not merely for current use but also for future uses (Dasgupta 2021). The more biodiversity there is, the more likely it is one could find the necessary information for curing illnesses, developing high-yield and robust agricultural crops, and so on. Ecosystems are characterised by highly non-linear, discontinuous, and discrete changes in their ecological 'resilience', that is, in their ability to 'recover from and thus absorb' (Barbier et al. 1994, p. 17) external and internal shocks. Although certain so-called keystone species play a role in maintaining diversity, the stability of an ecosystem ultimately depends on the extent of its resilience and not so much on the stability of individual components (Turner 1995). Yet, given widespread uncertainty, an ecosystem might be able to cope with piecemeal destruction for quite a long time, only to break down unexpectedly fast after some (often unknown) threshold has been transgressed and it loses its self-organising capacity. In some sense, every small-scale destruction increases the likelihood of unravelling the whole ecosystem (Randall 1991, p. 65).

Ceteris paribus, therefore, the more biodiversity there is, the higher its evolutionary potential and the bigger the opportunity-set open to future generations (Perrings 1994). Hence, there is a good case for regarding biodiversity as a critical form of natural capital and therefore for preventing large-scale biodiversity loss. On the other hand, this does not imply that if we do not preserve the totality of ecosystems and their biodiversity, we shall lose their basic life-support functions and make human life on Earth impossible. Losing some of the existing biodiversity would mean losing some of its use, some of its informational and insurance value in exchange for the benefits of depletion, but it would not mean that human life is at risk. The problem with widespread uncertainty about the extent of biodiversity loss and its consequences is that no one knows how much more biodiversity can be 'safely' lost without endangering the future of humankind.

Climate change and biodiversity loss are two examples where uncertainty is at its most striking. In other areas, uncertainty may be less striking but is still pervasive. There is typically uncertainty about damage costs from environmental pollution, including the extent to which such damages are highly non-linear in the amount of pollution generated. Uncertainty about how damages extend over very long time periods, which raises the issue of the 'right' discount rate, and uncertainty about the extent to which emissions result in irreversible damages applies to a large number of pollutants (Faucheux and Froger 1995; Pindyck 2007; LaRiviere et al. 2018). There is typically less uncertainty about the costs of reducing environmental pollution than there is about the costs of pollution (the environmental damages pollution generates) but these, too, are not known with certainty.

4.2.3 Ignorance

Ignorance refers to a situation where we have no idea whatsoever about the set of possible states of the world, about the probability distribution over the set, or about the resulting payoffs.[3] A weaker definition would allow for subjective beliefs where those beliefs are largely ambiguous or even arbitrary, however, and lack a sound scientific foundation.

Our knowledge about the extent and the likely consequences of the destruction of biodiversity resembles more a situation of ignorance than of uncertainty. A highly cited study from 2011 puts the total number of species on Earth and in the oceans at approximately 8.7 million, with a standard deviation of 1.3 million around this central estimate. Crucially, the authors point out that 'some 86% of existing species on Earth and 91% of species in the ocean still await description' (Mora et al. 2011, p. 1). Even our knowledge about most of the named species is only rudimentary (Troudet et al. 2017). We know only relatively little about the biological and socio-economic consequences of large-scale destruction of biodiversity, despite progress being made in the valuation of such loss (Dasgupta 2021). Especially, by their very nature, one cannot know the value of still undiscovered species that become extinct. As Norton (1986, p. 203) rightly argues, 'it is an understatement to refer to this level of ignorance as mere "uncertainty"'.

Climate change is another example where ignorance is pervasive. I have introduced it under the heading of uncertainty above. However, as an early report of the IPCC (IPCC 1996, p. 161) pointed out back in 1996: 'when dealing with many of the effects of climate change, ignorance is perhaps a more appropriate concept than uncertainty'. Nearly 30 years later, the IPCC prefers using the language of 'deep uncertainty' rather than ignorance and stresses it mostly in the context of sea level rise and Antarctic ice sheet loss. It is otherwise at pains to stress that 'deep uncertainty' is not a core concept in its reports (IPCC 2021, p. 40), presumably to present to the world the value of all the money spent on climate science. Nonetheless, the lesson remains that multiple features of climate change have aspects of both uncertainty and ignorance.

Also, ignorance has in the past been quite common for environmental problems: DDT (Kinkela 2011) and CFCs (Andersen and Sarma 2012) were both thought to be benign for the environment before their detrimental effects were discovered. Ignorance is arguably a pretty good description of the quality of our knowledge about the consequences of human activity on the state of the environment in the very long run.

4.3 COPING WITH RISK, UNCERTAINTY, AND IGNORANCE

How can policymakers cope with the existence of risk, uncertainty, and ignorance? In examining this question, I will make reference mostly to biodiversity and climate change.

4.3.1 The Precautionary Principle

One strategy to combat uncertainty and ignorance is to invest in research to gain better information on the set of possible states, their payoffs, and the probability distribution over the set of states. Climate science has made remarkable inroads into a better understanding of the consequences of human-induced climate change (IPCC 2021). However, for cases of uncertainty in general and for climate change in particular, it is not possible to convert a setting of uncertainty into a situation of mere risk. In most cases, significant doubt about the correctness of beliefs remains, either because the objective values cannot be known in principle or the costs of getting to the correct values are 'too high' from an information costs perspective, where 'too high' means a region where the marginal costs of information gathering are (far) higher than the marginal benefits.

Since uncertainty remains widespread, the so-called 'precautionary principle' has been invoked to deal with it. O'Riordan and Jordan (1995), Randall (2011), and Persson (2016) list a whole range of core elements of the precautionary principle, but there are two elements that are arguably the most important ones. First, *preventive* measures should be undertaken before there is *definite* scientific evidence 'proving' that a certain human activity causes environmental degradation. The motivation is to avoid regretting environmental inaction after unacceptable, irreversible environmental destruction has already taken place. As environmentalists emphasise: it is better to be vaguely right in time than precisely right too late. Second, and related to the first point, the burden of proof should shift to those who believe that an economic activity has only negligible detrimental consequences on the environment; that is, the new default position should favour environmental preservation, whereas current practice by and large favours economic activity over the environment. The precautionary principle can thus be interpreted as an insurance scheme against uncertain future environmental catastrophes. Hartzell-Nichols (2017) provides a book-length exploration of how the precautionary principle can be employed to call for ambitious reductions in greenhouse gas emissions to avert climate catastrophe.

The precautionary principle was first integrated into official policy statements in the 1970s in former Western Germany in the form of the so-called *Vorsorgeprinzip* (Boehmer-Christiansen 1994). It soon found its way into virtually every official document on the environment and appeared in countless international environmental treaties (Cameron and Wade-Gery 1995). The European Union (EU) has been a particularly strong adopter (Read and O'Riordan 2017). Some of this seeming 'success' of the precautionary principle was due to the fact that very often its application was merely rhetorical and did not change anything substantial. As Bodansky (1991) observes, part of the reason for this might be because the precautionary principle is not able to give a clear answer on when it should be applied; that is, what are acceptable and unacceptable environmental dangers, at what costs it should be applied, and what types of precautionary actions should be undertaken. In fact, the precautionary principle has been criticised by many as either trivial and vacuous if it is interpreted in a weak and vague way or as overly restrictive if it is interpreted in a strong or strict way (Powell 2010; Steel 2015; Sunstein 2021). As Cass Sunstein (2021, p. 25) put it: 'If we take costly steps to address all risks, however improbable they are, we will quickly impoverish ourselves.' The seeming success of the precautionary principle is likely due to policymakers adopting a rather weak version of it. How else would one explain that the precautionary principle has been adopted by all member countries of the United Nations as Principle 15 of the Rio Declaration on Environment and Development in 1992 when in reality it seems to have made very little difference to the state of environmental affairs in the vast majority of these countries?

4.3.2 Safe Minimum Standards

Another concept related to the precautionary principle comes in the form of SMSs. Propositions to introduce SMSs date back to Ciriacy-Wantrup (1952) and were originally reserved for issues of species preservation and biodiversity protection. However, the notion of SMSs has been used for other environmental topics as well. IPCC (1996, p. 159), for example, speaks of an 'affordable safe minimum standard' for the reduction of greenhouse gases. In a similar vein, more than two decades later IPCC (2019, p. 44) states clearly: 'Warming of 1.5°C is not considered "safe" for most nations, communities, ecosystems and sectors and poses significant risks to natural and human systems as compared to the current warming of 1°C.'

Returning to species protection, in its original application, SMSs call for granting a species some minimally viable standard. As originally introduced by Ciriacy-Wantrup (1952), no explicit qualification was made with respect to an upper limit on preservation costs. Later, however, SMSs were interpreted as calling for imposing a safe standard, as long as the economic costs of doing so are not ‘unacceptably high’. Note that the costs of protection are net of (expected) preservation benefits, where in the case of uncertainty and ignorance, some best guess of the size of benefits must be made.

The Endangered Species Act in the US has many characteristics of an SMS (Castle and Berrens 1993, p. 122). This Act has been described as the ‘most ambitious piece of species-protection legislation ever enacted by a single nation’ (Ando 1998, p. 7). The US Fish and Wildlife Service has considerable leeway to intrude into property rights and impose conservation of endangered species on private agents. Economic actions that threaten the existence of endangered species are only allowed if ‘the benefits of such action clearly outweigh the benefits of alternative courses of action consistent with conserving the species in its critical habitat’ (US Congress 1978, p. 49).

SMSs were originally intended for the protection of single species. However, the major threat to species derives more from the destruction of broader habitats than from the direct exploitation of individual species. Consequently, it was acknowledged that only the sustainable management of habitat areas can ensure the long-term survival of species (Barbier et al. 1994, pp. 60, 62). Also, due to the complexity of ecosystems and our ignorance about their capacity for resilience, as described above, it is increasingly recognised that sustainable management that safeguards ecological thresholds must be flexible and cannot apply fixed rules like a fixed maximum (seemingly) sustainable yield (Holling 1995, p. 49). Strictly speaking, for many species there are ‘no definite ecological–biological safe minimum standards’ (Hohl and Tisdell 1993, p. 177) at all. Hence, SMSs now tend more and more to mean establishing a viable standard for whole ecosystems where the standard is set well above some supposed minimum level. Protecting ecosystems is also a rather difficult, and most likely expensive, task since misguided human manipulation of natural environments that reduces the resilience of ecosystems must be avoided (Holling 1995). It is far from clear whether the sustainable management of ecosystems is feasible and how it is to be carried out (Carpenter 1994). Human protection of species might run counter to natural forces displacing one species by another emerging species, which might or might not be good for ecosystem stability (d’Arge 1994).

4.3.3 Safe Operating Spaces within Planetary Boundaries

Similar to the concept of SMSs, but used in a much broader and more general sense, Rockström et al. (2009) have developed the concept of safe operating spaces within planetary boundaries. The basic idea of safe operating spaces is to limit human perturbation of nine global environmental functions and life-support systems to levels that can be considered safe, in terms of maintaining their stability and resilience. By contrast, going beyond safe operating spaces risks crossing planetary boundaries and perturbing these functions in a way that is 'without analog in human history' (Richardson et al. 2023, p. 1).

The nine global environmental functions and life-support systems for which the authors have established safe operating spaces within planetary boundaries are:

- Climate change
- Biosphere integrity (genetic diversity and functional integrity)
- Stratospheric ozone depletion
- Ocean acidification
- Biogeochemical phosphate and nitrogen flow cycles
- Land system changes (deforestation)
- Freshwater loss
- Atmospheric aerosol loading
- Release of potentially unsafe synthetic chemicals.

In their original 2009 assessment, three of these were already deemed to have been transgressed (climate change, biosphere integrity, and the biogeochemical cycle) by Rockström et al. (2009). A 2015 reassessment by Steffen et al. (2015) added land system changes (deforestation), while a 2023 revision by Richardson et al. (2023) suggests that the safe operating spaces for freshwater and for the release of potentially unsafe synthetic chemicals have also been breached, bringing the total number of planetary boundaries transgressed to six out of nine. That six boundaries have now been crossed is also confirmed by the inaugural Planetary Health Check report (Planetary Boundaries Science 2024), an initiative led by the Potsdam Institute for Climate Impact Research (PIK) and its Director Johan Rockström, lead author of the original report, which will check in on the planetary patient on an annual basis.

Not surprisingly, the concept of planetary boundaries has been embraced by many proponents of SS as it neatly maps onto their argument that some forms of natural capital are critical and their use and abuse must remain within certain boundaries (see, for example, Barbier and Burgess 2017, 2021; Randall 2022).

Equally unsurprisingly, other scientists have been critical of both the concept itself but, more often, of the specific nine global environmental functions and life-support systems chosen (why these and not others?), as well as where the actual boundaries for a safe operating space lie (see the studies reviewed in Biermann and Kim 2020). From an equity perspective, even those who are, in principle, sympathetic to the concept have lamented the lack of a social justice dimension (see, for example, Kate Raworth's [2017] famous *Doughnut Economics* book as well as her earlier intervention calling for a 'safe and just space for humanity' [Raworth 2012]). Here, however, I shall concentrate on the issue of opportunity cost, which applies equally to the precautionary principle, SMSs, safe operating spaces within planetary boundaries, or, in fact, other ways of identifying critical forms of natural capital in the face of risk, uncertainty, and ignorance.

4.4 THE PROBLEM OF OPPORTUNITY COST

Some scholars stress the total value that natural capital, and especially natural ecosystems and their biodiversity, has for human beings. Norton (1986, p. 205), for example, argues that this total value is virtually infinite:

> The value of biodiversity is the value of everything there is. It is the summed value of all the GNPs of all countries from now until the end of the world. If biodiversity is reduced sufficiently, and we do not know the disaster point, there will no longer be any conscious beings. With them goes all value – economic and otherwise.

Costanza et al. (1997) have provided what they regard as a conservative estimate of the total value of the world's ecosystems. They suggest that this value lies in the range of US$16–54 trillion as a minimum estimate, with a central estimate of US$33 trillion (or US$46 trillion in 2007 constant dollars). For comparison, Costanza et al. indicate global GNP to be about US$18 trillion per year, so the estimated value of the world's ecosystems is very large indeed. Also, in Costanza et al. (1997), the values for specific items whose magnitude they regard as likely to be infinite have been deliberately truncated to make them finite and to provide a lower bound estimate of the 'real' value. In a follow-up paper using updated data but the same methodology, Costanza et al. (2014) estimated the total value of the world's ecosystems to be even higher, namely, with a central estimate of US$125 trillion in 2007 constant dollars (as compared to US$46 trillion in their previous evaluation from 1997).

The main problem with such studies is that estimates of the *total* value of natural capital, or more concretely ecosystems, are not helpful in judging whether specific depletion decisions can be tolerated or lead to costs that are 'unacceptably high'. This is because such decisions are always about marginal values, not total values. All choices exclude potential alternative choices and therefore incur opportunity costs.

While not directly tackling decisions about marginal values either, at least more useful than looking at the total value of ecosystems is estimating the cost of preserving ecosystems and their biodiversity. The first thing to note is that the protection and preservation costs are likely to be high, even in terms of direct management costs, due to the complexity of safeguarding the resilience of an ecosystem. The Paulson Institute, in its 2020 *Financing Nature: Closing* *the Global Biodiversity Financing Gap* report, puts the following price tag on biodiversity protection: 'To reverse the decline in biodiversity by 2030, our analysis suggests that, globally, we need to spend between US$ 722–967 billion each year over the next ten years. That puts the biodiversity financing gap at an average US$ 711 billion or between US$ 598–824 billion per year.'[4] Although such figures should always be treated with care, they give some tentative indication of the very large magnitude of costs for biodiversity protection. Keep in mind that this only refers to one form of critical natural capital, albeit, arguably, one of the most important ones and, together with the global climate, one of the most expensive ones to preserve. As for climate change, the McKinsey Global Institute (2022, p. vi) estimates that the transition to a net-zero carbon world by 2050 would require an additional US$3.5 trillion of capital spending on an annual basis.

These estimates suggest that the direct cost of biodiversity protection, while very large, is much smaller than that of drastically reducing greenhouse gas emissions. The main costs of biodiversity protection arise in terms of indirect costs, however, due to blocking economic development in part of a nation's area. Perrings's (1994, p. 93) fear that protecting the current biodiversity 'may very well condemn future generations to progressive impoverishment, especially in the light of the continuing expansion of the global human population' might be overdrawn. But the dilemma of full biodiversity protection is that there are *definite*, *present, real* costs for *uncertain, future* and perhaps *intangible* benefits. Also, the actual protector will not be able to reap all of the potential future benefits because some of the benefits are positive externalities to other people in other countries, that is, the protection of biodiversity has to some extent the characteristics of a global public good. Consequently, there are powerful incentives to free ride on others' efforts for biodiversity protection. Since every potential protector has the incentive to free ride, none may have sufficient impetus to protect biodiversity.

The dilemma of opportunity costs being definite, present, and real, whereas the benefits of preservation are uncertain, future, and intangible is not exclusive to biodiversity protection. It applies equally to many other environmental issues, most notably climate change. There are basically two possible answers to this dilemma. One is a deliberate decision to ignore the opportunity cost. This is the SMSs as originally introduced by Ciriacy-Wantrup: SMSs are established independent of the costs.[5] Because many of the costs of biodiversity depletion are rather speculative but potentially very high, and because we do not know how much biodiversity is needed to keep up its basic life-support functions, one could decide to refrain from marginal decisions at all and opt for preserving the totality of remaining biodiversity, disregarding the costs of preservation.

Similarly, with respect to environmental pollution, Spash (1993, p. 127) postulates an 'inviolable right of future generations to be free of intergenerational environmental damages', which would imply that 'the current generation would be obliged to identify all activities causing long-term damages and ban them *regardless of the cost*' (p. 128, my emphasis). Still more generally, Costanza (1994, p. 394), based on uncertainty and ignorance, calls for preserving the complete stock of natural capital without qualification as regards the opportunity costs of preservation:

> While a lower stock of natural capital may be sustainable, given our uncertainty and the dire consequences of guessing wrong, it is best to at least provisionally assume that we are at or below the range of sustainable stock levels and allow no further decline in natural capital. This 'constancy of total natural capital' rule can thus be seen as a prudent minimum condition for assuring sustainability, to be abandoned only when solid evidence to the contrary can be offered.

The other possibility is to allow opportunity costs to influence the decision and to explicitly limit the costs society is willing to incur for biodiversity protection and pollution prevention. This is the SMSs as they became interpreted over time with the qualification that costs must not be 'unacceptably high'.

Beckerman (1994, pp. 194ff.) warns against ignoring opportunity costs:

> Given the acute poverty and environmental degradation in which a large part of the world's population live, one could not justify using up vast resources in an attempt to preserve from extinction, say, every one of the several million species of beetles that exist. For the cost of such a task would be partly, if not wholly, resources that could otherwise have been devoted to more urgent environmental concerns, such as increasing access to clean drinking water or sanitation in the Third World.

Jacobs (1995, p. 63) claims that, in practice, we are not faced with many choices of the 'preserve some obscure species' versus 'improve basic health care' type, but at least they cannot be ruled out in principle. While we might not want to preserve every beetle, as such, we might well want to preserve the totality of remaining tropical rainforests and other habitats where beetles reside if we can ignore opportunity cost. Hence, there will remain many cases where fundamental ethical conflicts arise. These ethical conflicts are exacerbated by the fact that the vast majority of the world's biological diversity exists in only a few nation-states that belong to the poorest of the world (Myers et al. 2000). There is no easy and simple answer on how to solve these difficult choices and trade-offs. I discuss this question further in the concluding section.

If one opts against ignoring opportunity costs, then SMSs call for preservation unless the costs are 'unacceptably high' and costs should be understood as opportunity costs net of the expected benefits of environmental preservation. In other words, SMSs should be built upon environmental valuation, not replace it. It is not an alternative to valuation efforts, but an extension and qualification of valuation.

Critics of SS like Bjorn Lomborg have been quick to point out that once opportunity costs are seriously taken into account, it becomes questionable whether scarce economic resources should be spent on preserving critical forms of natural capital. The Copenhagen Consensus Center (https://copenhagenconsensus.com/), which he founded and heads as its director, has pushed out report after report and book after book putting forward some economists' views, including those of some Nobel Laureates, that such scarce resources are better spent on tackling other issues, such as tuberculosis, malaria, chronic diseases, malnutrition, poor education, impediments to trade, lack of digital procurement, and insecure land tenure (Lomborg 2023). I do not argue that this criticism is correct. Not least, if the argument of SS proponents is correct that certain forms of natural capital are critical and non-substitutable, then the argument that investments in other areas generate a supposedly higher rate of return is not directly relevant. But Lomborg's critique does remind us that SS proponents face multiple challenges in making their arguments for why certain critical forms of natural capital should be preserved. Not only is there uncertainty about which forms of natural capital are truly critical. Not only is there uncertainty about how much depletion could occur before a particular form of natural capital becomes critical. But there is also the challenge of opportunity cost: Is a particular form of natural capital so critical that it justifies spending the direct and indirect cost of preservation?

4.5 CONCLUSION

In this chapter, I have shown that the combination of the distinctive features of natural capital with risk, uncertainty, and ignorance suggests the conclusion that there are good reasons for the non-substitutability of specific forms of natural capital. They make a persuasive case:

- for preventing large-scale biodiversity losses, deforestation, and for the protection of ecosystems and their habitats
- for preserving global environmental life-support resources, such as the global climate and the ozone layer
- for limiting the accumulation of toxic pollutants
- for staying within other planetary boundaries.

The case is strengthened by the fact that examples abound of negative interlinkages between environmental problems: deforestation often worsens loss of topsoil and land degradation and contributes to climate change; acid rain not only kills forests but also contaminates freshwater sources; ozone depletion contributes to climate change and some of the substitutes for CFCs have high global warming potentials.

In contrast, as Chapter 3 has shown, there seems to be much less reason for being concerned about natural capital as a provider of resource input for the production of consumption goods and services. The existing empirical evidence thus appears to support the non-substitutability assumption of SS more strongly with respect to the role natural capital plays in absorbing pollution and providing direct utility, whereas support is strong for the substitutability assumption of WS with respect to natural capital as a resource input into the production of consumption goods. Essentially, this chapter has further strengthened the conclusion from the previous chapter that empirical evidence seems to support more WS with respect to the 'source' side and more SS with respect to the 'sink' side of the economy.

Note, however, that in the case where SS seems to be supported by the empirical evidence, it strongly favours the second of the two interpretations SS was given in Section 2.3.2. That is, from an SS perspective, one would want to keep the physical stocks of certain forms of natural capital intact. In contrast, preserving natural capital in value terms is not a reasonable conclusion from the evidence, as it would not preclude that certain forms of natural capital that provide basic life-support functions are endangered. The complete destruction of the ozone layer and the large-scale disruption of the biogeochemical cycle of the atmosphere cannot be compensated for, even if other forms of *natural* capital are built up instead. An increase in the number of whales cannot substitute for a bigger hole in the ozone layer, for example. One could, of course, argue that the depletion value of life-support resources is very large or almost infinite so that preserving natural capital in value terms would necessarily prevent running down these resources. Consequently, the two interpretations of SS would coincide in their policy conclusions. However, it seems more reasonable to target specific forms of natural capital directly, if they are regarded as non-substitutable, rather than rely on the hope that preserving natural capital in value terms will achieve their preservation indirectly.

An additional problem is posed by the existence of opportunity costs. I have argued in this chapter that there are basically two options. One is to ignore opportunity costs. Potentially large, but still finite, present and real costs are incurred in order to prevent uncertain and future, but potentially virtually infinite, costs of natural capital depletion. The other option is to allow opportunity costs to play some role and to opt for the preservation of the identified forms of natural capital unless the costs are deemed 'unacceptably' high.

Which option to take? I have argued in favour of the latter option and against ignoring opportunity cost. I readily admit that the latter option does not provide complete insurance against the non-achievement of sustainability and catastrophic outcomes. With the latter option, there is always the possibility of an *ex post* surprise, that is, the danger that too much natural capital is depleted in spite of our *ex ante* expectation that this depletion of natural capital would not endanger sustainability. On the other hand, with the first option of preserving natural capital independent of the costs, there is also the clear danger of significantly reducing other opportunities for current and future generations. Beckerman and Pasek (1997, p. 72) are correct in suggesting that, in certain circumstances, it might be better ethically justified to spend scarce resources on health or education rather than on the preservation of natural capital: 'It is difficult to see in what way the environment is in some moral class of its own.' The point is that to ignore opportunity costs is to 'solve' these often awkward trade-off decisions by simply avoiding them or assuming them away.

I have come to this conclusion by arguing strictly with reference to risk, uncertainty and ignorance about the substitutability of natural capital. Interestingly, such a conclusion is largely compatible with a moderate deontological ethical position. Such a position would prescribe 'to avoid deliberate [environmental] harm except where there are overwhelming beneficial outcomes which go beyond a consequential threshold' (Spash 2002, p. 238). Properly understood, an economic approach conscious of the ubiquitous existence of trade-offs, but also conscious of the equally ubiquitous existence of uncertainty and ignorance, therefore need not clash with a more rights-based approach towards sustainability.

If one goes for the second option, then it must be decided what 'unacceptably high' costs are. This question has no scientific answer. Scientists cannot tell society what it should regard as 'unacceptably high' costs. It is an ethical and political question for which economics or any other science is ill-equipped to provide answers. Indeed, the question does not even have a general answer as it will be highly context-specific. Such a position should not be misinterpreted. Research can inform better decisions, and environmental valuation can provide better and more comprehensive information as techniques become refined. But it is hubris to believe that natural or social scientists can make the decision on what should be regarded as 'unacceptably high' costs in society's stead.

The next two chapters do not question the validity of either paradigm, as the previous two chapters have done. Instead, they take each paradigm for granted and ask whether WS and SS, respectively, can be measured in practice.

NOTES

1. There is no consensus on the use of these terms in the literature. Often, risk and uncertainty are used interchangeably. What I call uncertainty is often referred to as 'hard uncertainty' or 'Knightian uncertainty' after Knight (1921).

2. Another term often used for uncertainty is ambiguity (Dobbs 1991).
3. Another term for ignorance used by O'Riordan and Jordan (1995, p. 10) is indeterminacy.
4. https://www.paulsoninstitute.org/conservation/financing-nature-report/
5. It must be said, however, that Ciriacy-Wantrup did not subject SMSs to the qualification that costs must not be 'too high'; he always argued that the costs of preservation, if properly undertaken, would be relatively small (see Ciriacy-Wantrup 1952, 1971).

5. Measuring weak sustainability

In this chapter, I discuss whether WS can be measured in practice. Section 5.1 presents the change in a country's total wealth per capita as the theoretically correct measure of WS. The most comprehensive two datasets on the change in total wealth per capita compiled by the World Bank and the UNEP are then presented.

Section 5.2 discusses the Index of Sustainable Economic Welfare (ISEW), also known under the name Genuine Progress Indicator (GPI), as an alternative indicator of WS. Early ISEW/GPI studies tended to show a widening gap between GDP and the country's ISEW or GPI. This widening gap was, however, artificially generated by the methodology of these early studies and is the result of problematic assumptions and methodological errors. More recent studies, which avoid some or even all of these errors, come to more nuanced findings that differ from country to country. I argue that the ISEW/GPI promises too much in trying to measure both current or contemporaneous welfare and future-oriented sustainability, which is a hopeless undertaking. Section 5.3 concludes by critically assessing both the change in total wealth per capita and the ISEW/GPI as measures of WS.

5.1 CHANGE IN TOTAL WEALTH PER CAPITA

Recall that the fundamental idea of WS is whether the present generation at least maintains and ideally adds to the total capital stock available to future generations for their use. Given the substitutability assumptions built into the WS paradigm, the change in all forms of capital can be linearly added together to result in the summary change in total capital. Since population growth diminishes the total capital stock available for each person, the change in the total capital stock *per capita* is the relevant measure of WS. If the total capital stock per capita is increasing over time, a country is weakly sustainable. It is weakly unsustainable if the total capital stock per capita decreases over time.

This is exactly what the World Bank and, separately, UNEP set out to calculate for as many countries in the world for as long a time period as possible, with the most recent World Bank data published as part of its report on *The Changing Wealth of Nations 2021* (World Bank 2021) and the most recent

UNEP data published as part of its *Inclusive Wealth Report* (UNEP 2018a, 2023). For reasons that will become clear below, I will mostly focus on the World Bank data.

Changes in the total wealth per capita as the measure of WS is not where the World Bank started off in its original attempts to measure WS. Instead, it started by computing what was originally called genuine savings (GS) and what it later called adjusted net savings (ANS).[1] Conceptually, GS or ANS captures investment in all forms of capital that together make up total capital minus depreciation of all forms of capital. In other words, it captures the net investment (gross investment minus depreciation) in total capital stocks. Theoretically, GS or ANS, a flow measure, should therefore simply and fully capture the change in total capital, a stock measure. Accordingly, a positive change in the value of the total capital stock should equate to positive GS/ANS and, vice versa, a decrease in the value of the total capital stock should equate to negative GS/ANS.

The policy recommendation of keeping GS/ANS above zero can be interpreted as an extension of Hartwick's (1977) famous rule into a more general framework with multiple consumption goods and various forms of capital: invest in all forms of capital at least as much as there is depreciation of all forms of capital. Under certain conditions, one can show that an economy cannot be weakly sustainable if its GS rate is persistently below zero (Pezzey 2002a; Pezzey and Toman 2002a; Dasgupta 2009). Importantly, the reverse does not hold true: positive GS rates at any moment of time cannot be taken as an indication of WS, because positive GS rates could be the result of, for example, unsustainable resource management and underpriced natural capital (Asheim 1994, p. 262). If environmental and other externalities are not internalised, then existing prices and quantities differ from the optimal ones. Pezzey and Toman (2002b, p. 17) therefore suggest that 'sustainability prices and sustainability itself are related in a circular fashion: Without sustainability prices, we cannot know whether the economy is currently sustainable; but without knowing whether the economy is currently sustainable, currently observed prices tell us nothing definite about sustainability'. GS is thus a one-sided indicator of WS: negative rates indicate weak unsustainability, but positive rates do not necessarily indicate WS.[2] The same logic extends to changes in total wealth per capita as a measure of WS.

In reality, in the actual way GS/ANS is computed by the World Bank, it 'can differ significantly from changes in wealth' (World Bank 2021, p. 52). The reasons are somewhat technical and do not interest us further here. Instead, I will concentrate on explaining how the World Bank arrives at its estimates of total capital stock per capita since it has moved away from GS/ANS as the principal way of measuring WS.

How, then, does the World Bank compute changes in the total per capita capital stock? In short, it's complicated. So complicated that it takes a 90-odd-pages-long technical document to explain the methods and data used for the calculations (World Bank 2021). I will only sketch the very basics here and refer readers to this document instead for technical details. At the aggregate country level, in the World Bank's conception, total capital consists of:

Total capital = produced capital (man-made capital) + human capital + natural capital + net foreign assets

The value of produced or man-made capital is estimated based on what is known to economists as a 'perpetual inventory method' in which the capital stock in any specific year t is the previous year's capital stock depreciated at constant but differing rates for six different categories of produced or man-made capital plus the investment in produced or man-made capital in year t.

Human capital is valued as the present value of all the expected future labour income that the workforce in a country is expected to generate. Net foreign assets, which sum to zero at the global level, consist of a country's portfolio equity net assets, foreign direct investment net assets, debt and financial derivatives net assets plus foreign exchange reserves, where net assets comprise assets (demands on foreigners) minus liabilities (demands by foreigners).

Natural capital captures several energy resources (oil, gas, and coal) as well as mineral resources (bauxite, copper, gold, iron ore, lead, nickel, phosphate rock, silver, tin, and zinc). Note how many important non-renewable resources are not included, such as diamonds and rare earths. The value of non-renewable natural resource capital stocks is estimated as the present value of expected revenues minus costs from the resource over its lifetime, that is, until exhaustion. It is therefore a function of expected prices, expected costs, and expected reserves, which all change over time. Higher resource prices increase the value of the non-renewable natural resource capital stock, whereas higher costs of extraction decrease it. The larger the proven reserves, the more valuable the resource stock. Resource prices are notoriously volatile, which creates challenges. More importantly, perhaps, for fossil fuel reserves, which contain carbon and the burning of which generates the main climate-warming greenhouse gas carbon dioxide, it is questionable whether proven reserves comprise resources that will eventually be extracted. Will many of these reserves become what is known as 'stranded assets': resources that need to remain in the ground to meet climate change mitigation targets? A 2021 study published in *Nature* estimated that to remain within the 1.5°C global warming limit espoused by the 2015 Paris Agreement, 60 per cent of oil and gas reserves and 90 per cent of coal reserves would need to remain in the ground, that is, become unextractable and therefore stranded (Welsby et al. 2021).

In addition, the World Bank, somewhat heroically, estimates the value of forest resources, both for their timber and non-timber forest ecosystem services value, the value of agricultural land, both cropland and pastureland, the value of protected areas, the value of mangroves, including their role in preventing or mitigating coastal flooding, and the value of fisheries.

There are some rather glaring omissions from the World Bank's conception of what makes up the total capital stock as set out above. Not surprisingly, given the difficulty of measurement, social capital is excluded from the Wealth of Nations calculations. As for natural capital depreciation, note in particular that there is no accounting for the damage caused by environmental pollution, unless it is indirectly accounted for in the valuation of agricultural land and protected areas, which is however highly unlikely. This is true for environmental pollution with impacts at the national level but also those which have a global impact, such as carbon and other greenhouse gas emissions. This is more disappointing as attempts to measure the damage caused by carbon emissions had long since been part of the GS/ANS measures the World Bank had previously championed. The World Bank (2021, p. 9) acknowledges that it 'does not yet include the value of carbon retention and sequestration services as part of wealth embedded in biological ecosystems (for example, forests, soils, and oceans). Nor does it subtract the social cost of carbon from fossil fuels.' However, simply listing these under the heading 'Future Work and Unanswered Questions', as it does, is highly unsatisfactory.

This is not to say that wealth accounting for environmental pollution is easy to do. One problem is finding the right values, or 'shadow prices', for the monetary valuation of environmental damages. Transboundary and global pollution present other big challenges. According to the 'polluter-pays principle' it would be up to the country causing transboundary pollution to include the corresponding correction terms in its wealth accounting. Presumably, it was this Hamilton and Atkinson (1996, p. 678) had in mind when they reasoned that 'some portion of a given country's saving should, at least notionally, be set aside in order to compensate the recipients of the pollution emitted and transferred across international boundaries'.

On the other hand, if one realistically assumes that sovereign nation-states are unwilling to compensate other nation-states, it might be more reasonable to stick to the presumption that each country should strive to keep the value of its own capital stock at least constant, independent of whether capital deterioration is caused within its own borders or beyond. According to this rule, it would be up to the country receiving pollution to include the corresponding correction terms in its wealth accounts or else to try to compensate the emitting country for pollution reductions. One might regard this allocation rule as unfair, but it is not unusual that countries refuse to pay according to the 'polluter-pays principle' if they cause transboundary pollution.

With global pollution, it is often rather difficult to say who is the victim and to what extent, and who is not. In dealing with problems like climate change, it might be reasonable to demand that every country is accountable for its own current greenhouse-relevant emissions. This conclusion is not compelling, however, especially if there is a history of emission accumulation. To give an example, developing countries are likely to resist being accountable for their full current emissions when it is the relatively much higher past emissions of the now-developed countries that are mainly responsible for the *current stock* of greenhouse-relevant emissions. Along these lines, Neumayer (2000a) argues in defence of historical accountability for greenhouse gas emissions. Such a principle, however, is likely to be resisted by developed countries. Hence, there is no straightforward allocation rule in this case. The problem is that there has to be some international agreement on allocation rules. If not, double counting as well as no counting at all is likely to occur. This is not a question of mere accounting; it really is about who is responsible for accumulating other forms of capital for environmental deterioration caused by pollution.

The methodology underlying the UNEP measures of total wealth per capita, or what it refers to as inclusive wealth per capita, is similar in some respects to the World Bank methodology but also rather different in other respects. Annoyingly, neither the World Bank nor UNEP ever engages directly with how their methodologies differ from each other and why. As far as produced capital (man-made capital) is concerned, the two methodologies are very similar. The valuation of natural capital is rather different, however, particularly for non-renewable resources, which matter greatly for the valuation exercises. Recall that the World Bank values the non-renewable resource stock as the present value of expected revenues minus costs from the resource over its lifetime, that is, until exhaustion. By contrast, UNEP values it as price minus average cost of extraction times the resource stock (UNEP 2023, p. 64). Conceptually, changes in human capital appear similar in both methodologies. Recall that the World Bank values human capital as the present value of all the expected future labour income that the workforce in a country is expected to generate. UNEP estimates the expected years of schooling for a population and then the returns to this education over the expected years of work. Whereas the World Bank takes a nation-state's net foreign assets into account, UNEP does not. Whereas UNEP takes damage from carbon emissions into account (UNEP 2018b, p. 15), the World Bank does not. UNEP also credits oil exporters with oil capital gains and oil importers with a corresponding oil capital loss (UNEP 2018b, pp. 15ff.), though why this only applies to oil and not to other fossil fuels or even minerals and metals is entirely unclear. Crucially, UNEP includes a measure of total factor productivity, which is a measure of capital-neutral technological progress, that is, technological progress that is not embodied in forms of capital, particularly produced (man-made) capital (UNEP 2018b, p. 16).

Based on the preceding paragraph, one may expect some differences between the World Bank and UNEP estimates. But one would not necessarily expect there to be massive differences. Unfortunately, as shown by McLaughlin et al. (2024), who also provide a more detailed comparison between the two methodologies, the differences are very large indeed. The overall correlation between the two measures for those data points with overlap is only 0.144, which is surprisingly low. Many more countries appear to suffer from negative changes in inclusive wealth per capita according to UNEP than from negative changes in total wealth per capita according to the World Bank measures (McLaughlin et al. 2024). Regional and income groups fare far worse according to the UNEP data than according to the World Bank (UNEP 2023, p. 97). In fact, the world as a whole is barely weakly sustainable with an absolutely meagre average inclusive wealth per capita annual growth rate of 0.12 per cent over the period 1990 to 2019, which translates to a total increase over this period of only 2.3 per cent. This stands in stark contrast to the World Bank (2021) estimate of a 44 per cent increase in total wealth per capita over the period 1995 to 2018. Even the region of East Asia & the Pacific, with its tremendous investments in man-made and human capital, is barely on a weakly sustainable trajectory according to UNEP estimates. With an average annual growth rate of 0.06 per cent it barely increases its inclusive wealth per capita from 1990 to 2019 by 1.1 per cent in total. Contrast this to the World Bank's estimate that this region increased its total wealth per capita by 139 per cent over the period 1995 to 2018. The UNEP estimates are rather implausible.

In the following, I will focus on the World Bank measures. UNEP does not provide a database with its empirical estimates for individual countries. For the 2018 *Inclusive Wealth Report*, the data can only be found in an appendix to a pdf document (UNEP 2018c). For the 2023 *Inclusive Wealth Report*, no data for individual countries are published in any form at the time of writing this revision of the book (October 2024). In fact, the 2023 *Inclusive Wealth Report* itself is extremely hard to find and not directly signposted on the UNEP website. None of this is as it should be.

With these caveats in mind, let us turn to what the empirical measurements on the change in the World Bank's total capital stocks per capita tell us about whether countries and the world as a whole are assessed to be weakly sustainable or not. Table 5.1 displays the percentage change in total capital stocks per capita as well as the manufactured, human, and natural capital stocks per capita components over the period 1995 to 2018. It does so for the world as a whole as well as for selected aggregate income groups (high-income OECD, other high-income, upper-middle-income, lower-middle-income, and low-income

Table 5.1 Percentage change in wealth per capita, 1995 to 2018

Income/Regional group	Total	Man-made	Natural	Human
World	+44	+38	+26	+49
East Asia & the Pacific	+139	+139	+65	+140
Europe & Central Asia	+36	+31	+23	+40
Latin America & Caribbean	+41	+45	+8	+49
Middle East & North Africa	+39	+65	+39	+16
North America	+29	+31	+17	+33
South Asia	+135	+196	+149	+243
Sub-Saharan Africa	+19	+15	-36	+56
High-income (non-OECD)	+27	+63	+15	+9
High-income (OECD)	+33	+36	+30	+33
Upper-middle-income	+179	+148	+44	+225
Lower-middle-income	+78	+87	+12	+97
Low-income	+22	+33	+72	+60

Source: World Bank (2021).

countries) as well as regional groups (East Asia & the Pacific, Latin America & the Caribbean, Middle East & North Africa, North America, South Asia, and Sub-Saharan Africa).

Results suggest that, at this level of aggregation, the world as a whole is safely weakly sustainable, as are all income and regional groups. Some income groups improve their WS more strongly than others. The same holds for some regional groups. But the predominant message is that not only is there sufficient net investment in produced and human capital, but even when it comes to natural capital, its per capita value has increased in all groups except for the set of countries located in Sub-Saharan Africa.

The picture does not look quite as rosy at the level of individual countries. Clearly, in income or regional group aggregation, the weak unsustainability of one country can be masked by the WS of one or more other countries. The World Bank (2021, p. 16) does flag that 26 countries 'saw a decline or stagnation in per capita wealth as population growth outpaced net growth in asset value, especially in Sub-Saharan Africa among countries such as the Democratic Republic of Congo, Niger, and Zimbabwe'. Let us take a closer look at three of these countries, namely, the Democratic Republic of Congo (DRC), Zimbabwe (both mentioned in the World Bank quotation) but also Saudi Arabia. Table 5.2 provides more detailed information on how their total

Table 5.2 Percentage change in wealth per capita (selected countries), 1995 to 2018

Capital stock	DRC	Saudi Arabia	Zimbabwe
Total wealth p.c.	-28	0	-20
Population	+102	+81	+27
Man-made capital p.c.	-5	+72	-6
Natural capital (renewable) p.c.	-49	-51	0
Natural capital (non-renewable) p.c.	+145	-4	-84
Human capital p.c.	+3	-29	-18
Net foreign assets p.c.	(-80)	+37	(-3)

Note: The DRC and Zimbabwe shrink their negative net foreign assets per capita (p.c.) positions by 80 per cent and 3 per cent, respectively, which represents a positive contribution to change in total wealth per capita.
Source: World Bank (2021).

capital stock per capita as well as its components have changed over the period 1995 to 2018.

Both the DRC and Zimbabwe have seen significant declines in their total wealth stock per capita over that period. In the case of the DRC, this is predominantly driven by a significant deterioration in the value of its renewable natural capital stock, whereas in Zimbabwe the major loss occurs in the non-renewable natural capital stock. Neither country, according to these World Bank figures at least, managed to noticeably increase their produced capital stock per capita, while Zimbabwe additionally suffered a significant loss in the value of its human capital stock per capita, which remained more or less stationary in the case of the DRC.

The picture looks somewhat different for Saudi Arabia, one of the world's biggest oil producers. Rather than seeing a deteriorating total capital stock per capita, it falls into the category of stagnation with hardly any change over the period 1995 to 2018. According to the World Bank data, while its net investment in produced capital per capita is strong and the country builds up its net foreign assets per capita, no doubt fuelled by fossil fuel exports, both of the positive drivers for WS are insufficient to compensate for the small decline in the value of the non-renewable natural capital stock per capita, and more importantly for the more significant decrease in the human capital stock per capita. There is also a large decrease in the country's renewable natural capital stock, the largest decrease in fact, but renewable resources are of far less importance to Saudi Arabia's total capital stocks than non-renewable resources. Put simply, over this period of time, Saudi Arabia was insufficiently investing profits from its fossil fuel sector into the education and skills training of a relatively rapidly increasing population. It seems that the Crown Prince and de facto ruler of Saudi Arabia, Mohammed bin Salman, more commonly known as MBS, who took office in 2017, has understood this lesson, and his 2030 vision for his country envisions massive investments into produced and human capital. If that strategy pays off, one should see Saudi Arabia experiencing rising total capital stocks per capita.

5.2 INDEX OF SUSTAINABLE ECONOMIC WELFARE (ISEW) AND GENUINE PROGRESS INDICATOR (GPI)

A number of scholars have developed, as a competing indicator of WS, the so-called ISEW, as it was originally called, and later on became more commonly known under the name GPI. The ISEW/GPI is intended to eventually replace a country's gross national product (GNP) or gross domestic product (GDP).[3] ISEWs/GPIs have been developed out of the concern that GNP/GDP is not an adequate indicator for either current welfare or sustainability. From this perspective, GNP/GDP is flawed because, among other things, it does not take into account (a) the value of household labour, (b) the welfare effects of income inequality, (c) the effects of environmental degradation on welfare and sustainability, and (d) it considers 'defensive expenditures' wrongly as contributions to welfare.

The ISEW/GPI stands in a long tradition and, indeed, partly builds upon earlier attempts to provide a more comprehensive indicator of welfare and to incorporate environmental and/or sustainability aspects into such an indicator – see, for example, Nordhaus and Tobin's (1972) *Measure of Economic Welfare* (MEW), Zolotas's (1981) *Economic Aspects of Welfare* (EAW) and Eisner's (1990) *The Total Incomes System of Accounts* (TISA). The MEW and the EAW take some environmental aspects into account. The MEW adjusts the welfare measure for 'disamenities of urban life' such as 'pollution, litter, congestion, noise' based on hedonic valuation studies.[4] The EAW subtracts air pollution damage costs together with half of the estimated control costs for air and water pollution and the full control costs for solid wastes from the welfare measure. It also deducts the costs of resource depletion. The TISA, on the other hand, does not include any environmental aspects in its measurement, but like the MEW and the EAW seeks to broaden the concept of capital and investment accounted for. For an overview, see Eisner (1988, 1990).

Computation of an ISEW/GPI usually starts with the value of personal consumption expenditures, which is a subcomponent of GNP/GDP. Consumption expenditures are weighted with an index of 'distributional inequality' of income (usually a modified Gini coefficient). Then, certain welfare-relevant contributions are added, and certain welfare-relevant losses are subtracted. Unfortunately, there is no consistent methodology that is applied across different studies, which means comparing the results from different studies is like comparing apples with oranges.

To illustrate this, let us look at the GPI for Iceland (Cook and Davídsðóttir 2021) and the GPI for 15 EU countries (Van der Slycken and Bleys 2024). Box 5.1 lists the items that are added or subtracted to arrive at the GPI. Clearly, there is a significant lack of overlap in the two approaches in terms of which items are included or excluded. The GPI for EU countries appears more clearly focused on sustainability, while the GPI for Iceland is much more comprehensive in terms of items included that affect current welfare. This makes comparisons between the two next to impossible even before one takes into account that they employ rather different methodologies for valuing any one item that is included in both approaches.

BOX 5.1 HOW GPIs FOR 15 EU COUNTRIES AND FOR ICELAND DIFFER IN THEIR COVERAGE

EU countries (Van der Slycken and Bleys 2024):

- Household consumption expenditures (+)
- Unpaid work (+)
- Defensive, intermediate, and rehabilitative private expenditures (–)
- Cost of consumer durables (–)
- Services of consumer durables (+)
- Shadow economy (+)
- Welfare losses from income inequality (–)
- Non-defensive government expenditure (+)
- Cost of air pollution (–)
- Ecosystem costs of nitrogen pollution (–)
- Cost of climate breakdown (–)
- Cost of extreme weather events (–)
- Depletion of non-renewable energy resources (–)
- Costs of use of nuclear power (–)
- Net capital growth (+)

Iceland (Cook and Davídsðóttir 2021):

- Household consumption expenditures (+)
- Costs of food waste (–)
- Insurance (–)
- Alcohol, tobacco, and narcotics consumption (–)
- Costs of family changes (–)
- Costs of maintaining dwelling services (–)
- Cost of consumer durables (–)

- Household repairs and maintenance (−)
- Income inequality adjustment (−)
- Public provision of goods and services (+)
- External benefits from higher education (+)
- Research and development (+)
- Value of leisure time (+)
- Value of unpaid labour in the volunteering sector (+)
- Recreation, culture, and religion (+)
- Community development (+)
- Services from natural capital (+)
- Services from built/produced/manufactured capital (+)
- Non-renewable resource depletion (−)
- Ozone depletion (−)
- Overharvesting of fisheries (−)
- Avoided depletion of biodiversity and landscape (+)
- Air pollution (−)
- Climate change contribution (−)
- Solid waste (−)
- Pollution abatement expenditures (−)
- Unemployment (−)
- Crime (−)
- Commuting (−)
- Vehicle accidents (−)

Once an ISEW/GPI has been computed, the policy recommendation is to ensure that the ISEW/GPI is not decreasing. One can interpret the ISEW/GPI loosely as a kind of extended or greened Net National Product (gNNP), which is defined as comprehensive consumption minus genuine savings or net adjusted savings (investment in all forms of capital minus depreciation of all forms of capital), which was introduced above in Section 5.1. Comprehensive consumption means that all utility-relevant items are included in consumption, not just consumption of material goods. It follows that the ISEW/GPI needs to measure more than is required for measuring WS: it aspires to also measure current welfare. The theoretical sustainability foundation of the ISEW/GPI follows from the fact that under certain assumptions preventing gNNP from falling is equivalent to preventing genuine savings or net adjusted savings from becoming negative (Pezzey and Toman 2002a, p. 184; Asheim 2003), which, as seen above, is a theoretically correct measure of WS. See also Lawn (2003) who argues for a theoretical interpretation of ISEW/GPI along the lines of Fisher's (1906) concept of capital and 'psychic income', which is an alternative to Hicks (1946), whose theoretical conception of capital and income is usually embraced by WS theorists.[5]

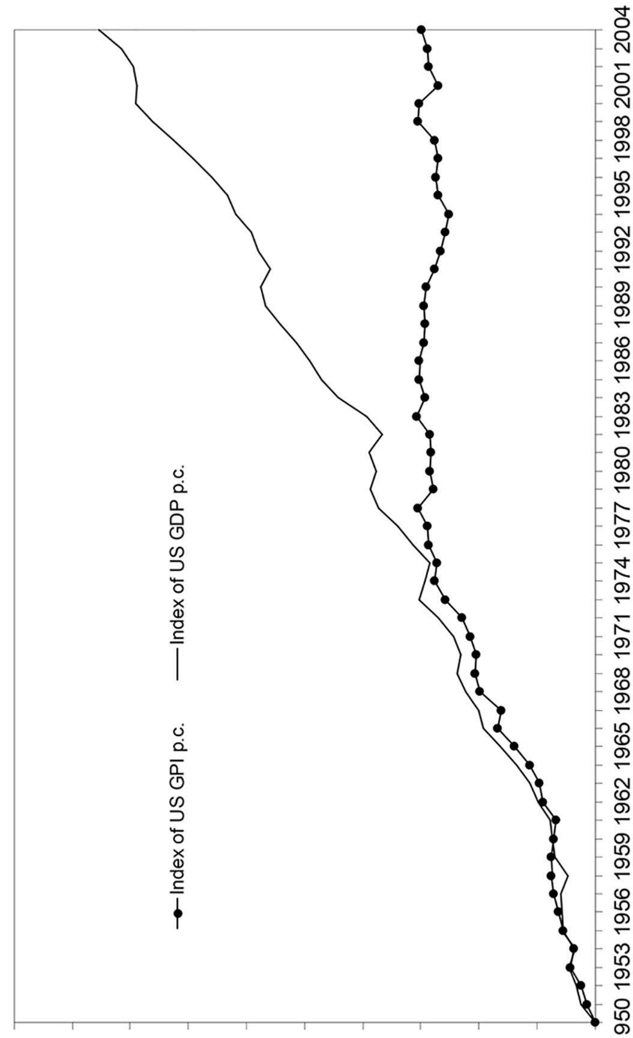
ISEW/GPI or related studies have been undertaken for, among others, Austria (Stockhammer et al. 1997), Australia (Hamilton 1999; Lawn and Sanders 1999;

Hamilton and Denniss 2000; Lawn 2008; Kenny et al. 2019), Belgium (Bleys 2008; Van der Slycken and Bleys 2024), Brazil (Andrade and Garcia 2015), Cambodia (Chhinh and Lawn 2007), Chile (Castañeda 1999), China (Lawn 2008; Guan et al. 2021), 15 EU countries (Van der Slycken and Bleys 2024), France (Nourry 2008), Iceland (Cook and Davídsðóttir 2021), India (Lawn 2008), Germany (Diefenbacher 1994; Diefenbacher and Zieschank 2010), Greece (Menegaki and Tsakarakis 2015), Israel (Kot 2008), Italy (Guenno and Tiezzi 1998; Armiento 2018), Japan (Lawn 2008), the Netherlands (Rosenberg et al. 1995; Bleys 2007), New Zealand (Lawn 2008; Patterson et al. 2012), OECD countries (Pais et al. 2019), Poland (Gil and Sleszynski 2003), Scotland (Moffatt and Wilson 1994), Spain (O'Mahony et al. 2018), Sweden (Jackson and Stymne 1996), Thailand (Clarke and Islam 2005; Lawn 2008), Turkey (Menegaki 2018), the UK (Jackson and Marks 1994; updated in Jackson et al. 1997), the US or US states (Daly and Cobb 1989; Cobb and Cobb 1994; Redefining Progress 1999, 2001, 2006; Talberth and Weisdorf 2017; Fox and Erickson 2020; Lazarus and Brown 2022), and Vietnam (Lawn 2008). Some studies for the sub-national level also exist.

Unfortunately, there is no consistent methodology that is applied across different studies. Instead, each study employs its own somewhat idiosyncratic view on what should be added and what should be subtracted. This renders comparisons of ISEW/GPI across countries (or other geographical units) next to impossible. Partly, such inconsistency across studies is driven by differences in data availability for different locations. Partly, however, it is driven by different views on what should and what should not enter a measure of both current welfare and WS.

What many early studies usually demonstrated is that the ISEW or GPI of a country has been growing much more slowly than its GNP/GDP and indeed has either not grown any further or has even fallen since the early 1980s or even 1970s. As an explanation for this widening gap between ISEW or GPI, on the one hand, and GNP or GDP, on the other, Max-Neef (1995, p. 117) put forward the so-called 'threshold hypothesis': 'for every society there seems to be a period in which economic growth (as conventionally measured) brings about an improvement in the quality of life, but only up to a point – the threshold point – beyond which, if there is more economic growth, quality of life may begin to deteriorate'. This 'threshold hypothesis' is referred to in almost every early study of ISEW or GPI and Max-Neef (1995, p. 117) himself regarded the evidence from these studies as 'a fine illustration of the Threshold Hypothesis'.

Figure 5.1 provides an example of the so-called threshold effect for the US from one such early study (Redefining Progress 2006). It shows the development of the US GPI per capita in comparison to GDP per capita from 1950 to 2004 in constant US$ of 2000, both indexed to 100 in 1950, at the start of the period, to allow an easy comparison of growth performance. Whereas in



Note: 'Corrected' means GPI without 3 per cent escalation factor for resource depletion and without accumulation of carbon dioxide damage (1950 = 100).
Source: Redefining Progress (2006) and corrections.

Figure 5.1 *Index of GDP, GPI and corrected GPI for the US* the beginning, the two graphs roughly move in parallel with each other, from around the 1970s, there is an increasing divergence: GDP is still increasing, but the GPI no longer is. This picture is typical for many early ISEW or GPI studies. For example, for Germany, Diefenbacher (1994, p. 228) finds after 1980 'ongoing growth of the GNP, but a rather sharp decline of the ISEW'. Also, typically two to three items are largely responsible for causing this increasing divergence between GNP/GDP and ISEW/GPI: resource depletion, long-term environmental damage, and, less importantly, a more unequal income distribution.

The early ISEW/GPI studies can be criticised for:[6]

- being arbitrary in the components they include or exclude, implicitly or explicitly, as contributors to welfare
- introducing income inequality measures that are necessarily highly subjective
- valuing long-term environmental damage and resource depletion in ways that by definition generate the 'threshold effect'.

One prominent item, defensive expenditures, provides a case in point for the first criticism. The concept of defensive expenditures is dubious and elusive since it is rather arbitrary what should count as defensive (Jacobs 1991, pp. 228–32). Early ISEW/GPI studies often excluded 50 per cent of expenditures for education because their authors believed that education 'contributes little to productivity'. This is clearly at odds with the importance attached by most economists to human capital and education. However, more relevant to this section here is that Cobb and Cobb (1994, p. 54) did not want to count education as consumption either since

> most schooling appears to be defensive. In other words, people attend school because others are in school and the failure to attend would mean falling behind in the competition for diplomas or degrees that confer higher incomes on their recipients.

Proponents of early ISEW/GPI studies have declared many other expenditures as 'defensive', that is, as merely protecting individuals against a decline of welfare caused by some other socio-economic activity. For example, Cobb and Cobb (1994) regarded 50 per cent of health expenditures as defensive and therefore not adding to welfare. The problem is that following this line of argument, one could classify many if not most expenditure items as defensive in character. For example, if health expenditures are defensive expenditures against illness, why should food and drinking expenditures not count as defensive expenditures against hunger and thirst? Are holiday and entertainment expenditures to be considered defensive expenditures against boredom? Should they all be subtracted from consumption expenditures?

Daly and Cobb (1989, p. 78) defend their concept of subtracting defensive costs by saying that '"defensive" means a defense against the unwanted side effects of other production, not a defense against normal baseline environmental conditions of cold, rain and so on'. But even accepting Daly and Cobb's definition, one could argue that at least part of food, drink, entertainment and holiday expenditures are caused by the stressful, exhausting, and boring modes of modern economic production that make these expenditures necessary as a defence against their unwanted side effects. As the revised *System of National Accounts* rightly retorts: 'Pushed to its logical conclusion, scarcely any consumption improves welfare in this line of argument' (Commission of the European Communities–Eurostat et al. 1993, p. 14).

As concerns income inequality, a fundamental critique is that the valuation of the distribution of income in a measure of welfare fails to command general agreement. This critique is well established. Already in 1994, Mishan (1994, p. 172) noted that 'all efforts to adjust the welfare index to accommodate changes in distribution … must be regarded with misgivings. They are either arbitrary or politically biased and are, therefore, invariably a focus of attack.' Of course, not undertaking any explicit valuation is tantamount to assuming implicitly that the marginal utility of income is constant and the same for the rich and the poor alike – an assumption which is admittedly no less arbitrary than the one embraced by the proponents of an ISEW/GPI.

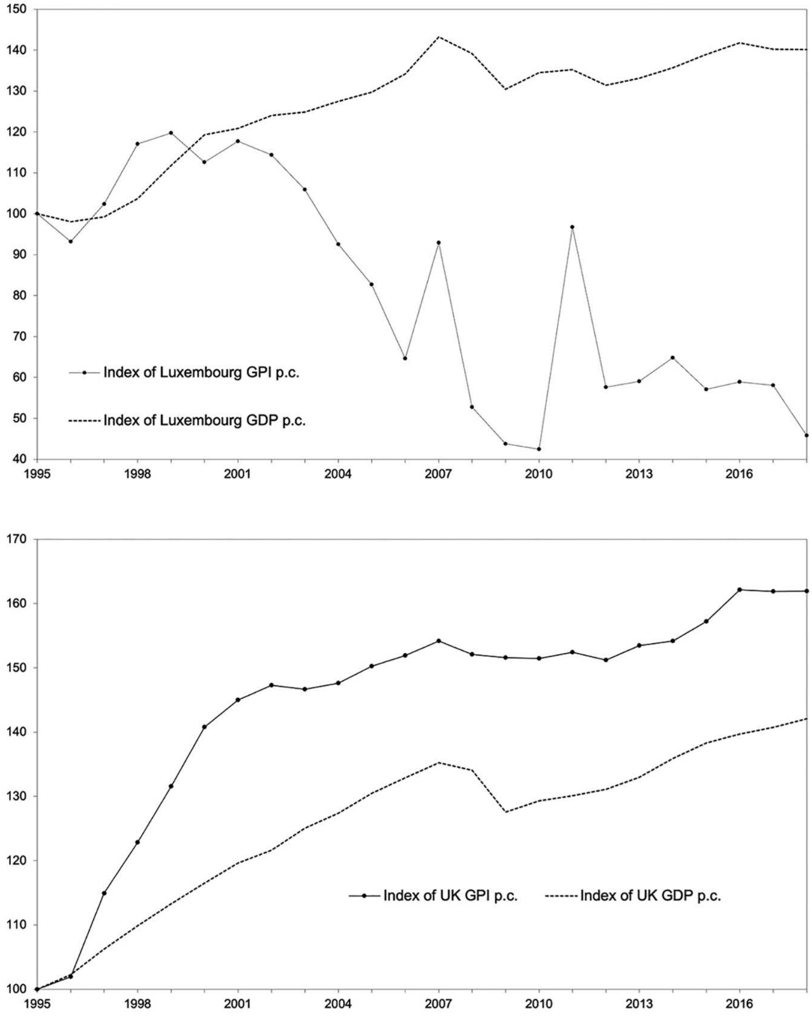
As concerns the valuation of long-term environmental damage, or the costs of climate change as this item is sometimes called, the fundamental question is whether this value should accumulate over time or not. With few exceptions (see, for example, Hamilton and Denniss 2000; Posner and Costanza 2011; Patterson et al. 2012), the authors of early ISEW/GPI studies have opted for accumulation, which is however methodologically flawed. Naturally, climate change is a problem of pollution stock, not of pollution flows, and the marginal social cost increases with the already accumulated stock of carbon in the atmosphere which remains resident for a very long time. However, to let the annual damage from carbon emissions accumulate year after year is a clear methodological error and it is very unfortunate that many authors of early ISEW/GPI studies continued committing this mistake, despite being aware of the criticism. Neumayer (2000b) has shown that if long-term damage from climate change is not assumed to accumulate year after year, then this item no longer contributes to a 'threshold effect', unless the marginal social cost of carbon emissions is assumed to increase strongly over time.

With regard to resource depletion, early studies differ in that some use the resource rent method, whereas others use the replacement cost method. Those using the resource rent method, such as Daly and Cobb (1989), Stockhammer et al. (1997), Diefenbacher (1994), and Guenno and Tiezzi (1998), deduct total resource rents from consumption expenditures. Cobb and Cobb (1994) were the first to use the replacement cost method instead. Each barrel of oil equivalent was valued at a replacement cost which was assumed to escalate by 3 per cent per annum between 1950 and 1990 and was anchored around an assumed cost of $75 in 1988. Castañeda (1999), Rosenberg et al. (1995), Moffatt and Wilson (1994), Jackson and Stymne (1996), Jackson et al. (1997), Hamilton and Denniss (2000), and Redefining Progress (1999, 2001, 2006) have all followed Cobb and Cobb's example with slight modifications, but Bleys (2008) has accepted the criticism put forward in Neumayer (2000b) and abandoned the escalation factor.

It is already questionable to assume that all non-renewable energy resource consumption needs to be replaced fully by renewable resources given that there are still huge reserves of non-renewable resources available for many years to come – see Section 4.4, p. 118. I will concentrate on the 3 per cent escalation factor, however, which clearly gives rise to a threshold effect. As a rationale for this assumption of constantly increasing replacement costs, Cobb and Cobb (1994, p. 267) refer to the costs per foot of oil drilling, which they report to have increased by about 6 per cent per annum during the period of high oil prices in the 1970s. This triggered the exploration and drilling of more difficult-to-exploit oil fields. They reason that 'when the limits of a resource are being reached, the cost of extracting the next unit is more costly than the previous unit' and that 'this principle presumably applies also to renewable fuels, though not as dramatically as to oil and gas', which is why the escalation factor is assumed to be 3 per cent instead of 6 per cent.

Yet, such reasoning is erroneous. Costs for renewable energy alternatives to non-renewable energy decrease rather than increase over time as technology improves and economies of scale kick in with expanding installation of renewable resources. Instead of assuming replacement costs to escalate by 3 per cent per year, it would therefore be more appropriate to assume that replacement costs are falling over time.[7] Neumayer (2000b) has shown that if replacement costs are not assumed to escalate and are simply kept stationary, then depletion of energy resources no longer contributes to a 'threshold effect'.

Fortunately, some of the more recent studies have avoided these methodological errors, which artificially create a threshold effect between GDP growth and GPI growth over time. A role model in this regard is the New Zealand GPI. Interestingly, Patterson et al. (2012) find that the country's GPI has grown but has grown more slowly than GDP over the period 1970 to 2006. Many, though not all, of the more modern ISEW/GPI studies above come to a similar conclusion. There is, however, also tremendous variation in empirical results. The already mentioned study for 15 EU countries by Van der Slycken and Bleys (2024) finds that the GPI per capita of these countries has changed between



Source: Van der Slycken and Bleys (2024).

Figure 5.2 Index of GDP and GPI for Luxembourg (upper) and the UK (lower)

1995 to 2018 from anywhere between -54.8 per cent for Luxembourg (see upper graph in Figure 5.2) to +67.1 for the UK (see lower graph in Figure 5.2) where, unusually, it has also outpaced growth in GDP per capita, which grew by 42.1 per cent over this period. Such stark differences in genuine progress performance between these two countries are hardly plausible, which casts doubt on the validity and reliability of the GPI methodology, despite in this case even being the same for both countries. Similarly, the somewhat wild fluctuations in the GPI per capita of Luxembourg over the study period do not instil confidence in the validity or reliability of the underlying methodology.

5.3 CONCLUSION

Can WS be measured? In theory, the answer is straightforward: of course, it can. Just measure how the value of the total capital stock per capita changes over time. If it increases (decreases), then the trajectory of the unit, typically a country, for which the measurement is taken is weakly sustainable (unsustainable). This is what the World Bank's Wealth of Nations and UNEP's Inclusive Wealth calculations try to put into practice. Do their published data provide a reliable empirical indicator of WS? On one level, the answer is clearly no. So many relevant items of natural capital in particular are still not included. So many dubious and simplifying assumptions need to be taken in order to come up with numbers purportedly claiming to value the wealth of nations.

On another level, however, I find it hard to contest the validity of the World Bank's general finding: that the world as a whole as well as aggregate regional and income groups are on a weakly sustainable trajectory and that there are only a few countries – typically natural resource-dependent ones like Saudi Arabia and/or countries marred by poor governance, conflict, and endemic corruption like the DRC and Zimbabwe – that potentially struggle to achieve WS. If all forms of capital are fully substitutable for each other – the fundamental premise of WS – then it is hard to see how most places do not achieve sufficient investment in produced and human capital to compensate for loss of natural capital and are therefore deemed to be weakly sustainable. McGrath et al. (2022) show that if one takes more air pollutants and the damage they cause to capital stocks into account, then some Eastern European countries exhibit negative genuine savings rates, an alternative measure of WS, over the period 1990 to 2016. However, while their study corrects some overestimation of genuine savings by more comprehensively accounting for natural capital depreciation, they do not correct for some underestimation of genuine savings due to other factors. In general, the problem lies in the questionable substitutability assumption of WS, not so much in inadequate measurement of WS given this assumption. In other words, I would contest that countries are sustainable as indicated by the World Bank measures not because these measures are inadequate in what they cover – though inadequate they are – but because WS is a fundamentally flawed and inadequate concept of sustainability with its assumption of perfect substitutability of all forms of capital.

The ISEW/GPI was introduced as a competing indicator of WS. Early studies painted a very pessimistic picture, but their results depended on a number of problematic methodological assumptions or outright methodological errors. A widening gap between ISEW/GPI and GDP/GNP was artificially created via the introduction of a 3 per cent cost escalation factor for non-renewable resource use and the accumulation of long-term environmental damage. With such assumptions built into the early ISEW/GPI studies, it is difficult to see how any country could escape running into the threshold effect sooner or later and see their ISEW/GPI either stagnating or even decreasing. More recent ISEW/GPI studies do not adopt the same problematic or, arguably, flawed methodological assumptions. They tend to find that the ISEW/GPI of many studies continues to grow, albeit at a slower pace than GDP/GNP.

Findings from more recent studies are also more mixed in the sense that the experience of different countries can differ quite strongly, as the study by Van der Slycken and Bleys (2024) has shown: the UK's GPI grows more strongly than its GDP, whereas Luxembourg's GPI nearly collapses despite continuing GDP growth. Such stark differences in 'genuine progress' in what are otherwise rather similar highly economically developed countries appear implausible and raise doubts about the construct validity and the reliability of the ISEW/GPI methodology.

In looking at the methodology of the early ISEW/GPI studies, one suspects that they were constructed with the very intention of producing the desired result of decreasing 'sustainable economic welfare'. Some of the problematic assumptions and methodological errors suggest that the proponents really object to WS and want to introduce SS somehow through the backdoor into the ISEW and GPI, which is, however, an indicator of WS, as readily admitted by Daly and Cobb (2007, p. 288), since it assumes that natural capital is substitutable. Indeed, it is rather striking that all the major early proponents of ISEW and GPI are also proponents of SS. For example, it is highly ironic that Herman Daly was one of the inventors of the ISEW, whereas, in all his other writings, he vehemently argued for the non-substitutability of natural capital.

One fundamental problem with the ISEW/GPI is that it tries to measure both WS and current welfare, and there is no objective answer on what factors that determine current welfare. It is therefore very subjective. If one includes a correction term for income inequality, why not include a correction term for other inequalities? Why not include a correction term for the degree of political freedom, a correction term for the extent of crime (as some studies have done), a correction term for the degree of equality between the sexes, or a correction term for the advancement of civil and other rights for homosexual people? A prominent item, which would raise economic welfare over time and is not included in the ISEW/GPI, is improvement in the quality of consumption goods, as this will not necessarily and fully be reflected in the value of personal consumption expenditures. Another very important item is increases in life expectancy due to better health care and progress in medical technology. Crafts (2002) estimates the additional welfare gain due to reduced mortality and finds that this raises the growth rate of a welfare measure by about 0.7 to 0.8 percentage points.

Some proponents of the ISEW are aware of the subjectivity of the numbers they produce, as becomes clear in the following quotation from Cobb and Cobb (1994, p. 252): ‘The point is rather that when the GNP functions politically as a welfare measure, it should not be allowed to masquerade as a measure that is somehow more objective than alternative ways of determining well-being.’ Also, Herman Daly, together with John B. Cobb, one of the first proponents of an ISEW, is aware of the many criticisms that can be raised against their measure. At the same time, however, he still sees the ISEW as a better indicator of ‘sustainable economic welfare’ than GNP and thus justified:

> Of course we had to make many arbitrary judgements, but in our opinion no more arbitrary than those made in standard GNP accounting – in fact less so. … We have no illusions that our index is really an accurate measure of sustainable economic welfare … . We did not offer the ISEW as the proper goal of economic policy – it too has flaws. If GNP were a cigarette, then the ISEW would be that cigarette with a charcoal filter. (Daly 1996, pp. 97ff.)

Similarly, Daly (1996, p. 115) acknowledges the difficulties in constructing a measure of welfare but sees the ISEW justified by preferring ‘even the poorest approximation to the correct concept’ to ‘an accurate approximation to an irrelevant or erroneous concept’. Yet again, at the same time, Daly realises and concedes that ‘the mere existence of any numerical index of welfare is a standing invitation to the fallacy of misplaced concreteness’ (p. 98).

Not only is the measurement of current welfare highly subjective, it is also questionable whether one single indicator can measure both current welfare and WS at the same time. For example, income inequality determines current welfare differently compared to sustainability. Non-renewable resource use should be measured differently in a measure of sustainability than in a measure of current welfare, and so on. As Stiglitz et al. (2009, p. 77) put it succinctly:

> The question of sustainability is complementary to the question of current well-being … and must be examined separately. This recommendation to separate the two issues might look trivial. Yet it deserves emphasis, because some approaches fail to adopt this principle, leading to confusing messages. The confusion reaches a

peak when one tries to combine these two dimensions into a single indicator. This criticism applies not only to composite indices, but also to the notion of green GDP. To take an analogy, when driving a car, a meter that weighed up in one single value the current speed of the vehicle and the remaining level of gasoline would not be of any help to the driver.

NOTES

1. The term 'genuine' was introduced by Hamilton (1994) to distinguish genuine savings, which refers to all utility-relevant stocks of capital including man-made capital, natural capital, human capital as well as (in principle at least) social capital, from traditional net savings, which refers only to man-made or produced capital.
2. Empirically, it has been shown that past GS rates can predict the sign, if not the magnitude, of future consumption growth (Ferreira and Vincent 2005; Ferreira et al. 2008) as well as future changes in social welfare more broadly as measured by the infant mortality rate and the human development index (Gnègnè 2009). But it is a relatively poor predictor, and one reason for this is the immense difficulty in measuring WS in actual practice.
3. The difference between GNP and GDP is that GDP includes output produced by foreigners within a country and excludes output produced by nationals abroad. Whenever I speak of GNP or GDP in the following, strictly speaking, it should read GNP/GDP.
4. Such studies derive the value from environmental disamenities by comparing, for example, house prices from real estate, which are similar in all respects except for the environmental disamenity.
5. See Harris (2007) for a critique of Lawn (2003). With the notable exceptions of Lawn (2003) and Brennan (2008), proponents of the ISEW/GPI and related indicators have devoted comparatively little effort to theoretically justifying their measures.
6. For a discussion of other problems of a methodological and conceptual nature, see, for example, Atkinson (1995), Neumayer (1999c, 2000b), and Ziegler (2007).
7. Lawn (2005, p. 204) defends the escalation factor with reference to price paths of non-renewable resources. But this is a misunderstanding, as the escalation factor must refer to the cost of renewable resources, not the cost of non-renewable resources. In fact, rising non-renewable resources prices are likely to bring down the costs (prices) of renewable resources, as Section 3.2 has shown.

6. Measuring strong sustainability

In this chapter, I will discuss several indicators put forward for measuring SS and explore the problems they encounter. Not all existing indicators of SS can be addressed. However, I will analyse what I regard as the most important ones. Section 6.1 covers two popular physical indicators, namely, ecological footprints (EF) and material flows, plus a perhaps less well-known but interesting and promising measure, the strong environmental sustainability index (SESI). These physical indicators do not bring any monetary valuation into the measurement. This is different with respect to hybrid indicators, looked at in Section 6.2. These try to combine physical standards with monetary valuation. Hybrid indicators have not really taken off since pioneering measures were proposed in the 1990s, predominantly because of the difficulties in empirical estimation.

6.1 PHYSICAL INDICATORS

These are indicators that do not undertake any form of monetary valuation. I analyse three physical indicators, namely, ecological footprints, material flows, and the SESI.

6.1.1 Ecological Footprints: Measuring Sustainability by Land Area

The concept of EF was originally conceived by Mathis Wackernagel and William Rees at the University of British Columbia in the early 1990s (Wackernagel and Beyers 2019, p. 11). It has, over time, become an incredibly well-known and often cited and referred to concept and measure. Rees and Wackernagel (2023, p. 6) claim that ‘in the three decades since it was formally introduced, the EF metric has become one of the world’s best-known metrics of humanity’s (un)sustainability’. With millions and millions of hits for EF in results from internet search engines and many policymakers referring to EF when making statements about the environment, including the Secretary-General of the United Nations (p. 6), it is hard to quibble with this claim.

The concept of EF focuses on environmental sustainability rather than inter-generational equity more generally. Its objective is to translate all the ecological impacts of human economic activity into the 'area required to provide the resources we use and to absorb our waste' (WWF 2008, p. 14), subject to the 'predominant management and production practices in any given year' (Wackernagel et al. 2002, p. 9266). EF can be calculated for individuals, cities, regions, countries, or the world as a whole. Rees and Wackernagel (2023, p. 7) define the consumption-based EF of the population of a city, region, country, or the world as a whole as follows:

> The total area of productive ecosystems that the population requires, on a continuous basis, to produce the bio-resources it consumes (e.g., plant-based food and fiber products, livestock and fish product, timber and other forest products, space for urban infrastructure) and to assimilate its wastes, particularly carbon dioxide emissions, wherever on Earth the relevant ecosystems are located.

Neither waste production, nor toxic releases, nor freshwater withdrawal are included. Also, the extraction of non-renewable mineral resources is not included at all, and non-renewable energy resources are taken into account only with respect to the land area required to hypothetically absorb carbon dioxide emissions from fossil fuel burning. The reason is probably that it is difficult to convert non-renewable resource extraction into a required land area.

Obviously, not all bioproductive land is the same. All land area is therefore standardised across land types, regions, and time into one common global measurement unit (so-called global hectares) using yield and equivalence factors. Equivalence factors make different categories of land use roughly comparable with each other, whereas yield factors make land of the same land-use category, but with differing productivity, comparable. Proponents of EF emphasise that, wherever possible, they use publicly available government-approved data and that their calculations are conservative in the sense of under- rather than overestimating the EF (Wackernagel and Silverstein 2000; Wackernagel and Yount 2000; Wackernagel et al. 2002; Rees and Wackernagel 2023).

Of all the human impacts, accounting for the carbon footprint from fossil fuel burning is the most important one, responsible for circa 60 per cent of the global EF in the most recent calculations (WWF 2022). This so-called energy or carbon footprint is the one that has grown fastest over time and in which the disparity between the developed and developing countries is largest. It is also the most contested component of EF, however. It is calculated as the forest land area required to hypothetically sequester enough carbon from the atmosphere to avoid any increase in the atmospheric concentration of carbon. This is done under the assumption that about 35 per cent of carbon emissions are absorbed by the world's oceans[1] (Wackernagel et al. 2002). Electricity generated from nuclear power plants was first excluded, then for some time it was included in the EF and measured as the land area required to sequester the carbon equivalent if the electricity from nuclear energy were produced with fossil fuels instead. It then became excluded again, however, in order 'to improve methodological consistency' (WWF 2008, p. 14).

The EF is linked to the somewhat older concept of a sustainable population size. If the EF of a country, for example, exceeds the bioproductive land area available, then this can also be interpreted to mean that the area's population is bigger than its sustainable size.[2] Ironically, from this perspective, there would be unsustainable 'over-population' in the developed countries, which, as I will show below, typically have ecological deficits, rather than in the developing countries. Proponents of EF usually do not emphasise the link to sustainable population size, however, possibly because they want to stress that consumption levels causing the high EF are unsustainable rather than blaming 'over-population'. Having said that, Wackernagel and Beyers (2019, pp. 89–92) recognise that reducing the global population is one of four factors that can bring unsustainable footprints back within the available biocapacity – the other three being reducing the footprint per person, restoring and nurturing biocapacity, and increasing the productivity of the available land area.

As the focus is on consumption, the required land area is attributed to the consumer rather than the producer since the consumer rather than the producer is deemed responsible for the impact. That is, for example, resources extracted in a developing country but exported to a developed country count towards the EF of the developed country (Syrovátka 2020). This stands in stark contrast to the allocation rule for the World Bank's measure of the change in the value of the total capital stock per capita, discussed in Section 5.1. Both allocation rules make sense in their own way: EF is interested in whose consumption creates an EF, whereas the World Bank's measure of WS is interested in determining whether the extracting country manages to prevent the value of its total capital stock per capita from declining. Land, rather than money, is taken as the unit of accounting in EF since, according to its proponents, 'monetary analysis is misleading as it suggests substitutability, allows for the discounting of the future and focuses on marginal rather than absolute values' (Wackernagel et al. 1999, pp. 376ff.). EF is regarded by its proponents as an indicator in the spirit of SS.[3]

If the EF exceeds the bioproductive land area available, then the carrying capacity of the land area is exceeded. This is called an ecological deficit and the economic activity causing the EF is judged to be strongly unsustainable. According to Wackernagel and Beyers (2019, p. 86), the world's total EF started to exceed the world's total biocapacity around the year 1970, and this excess gap has more or less continuously widened since then. On this measure, the world is clearly on a strongly unsustainable trajectory.

It is perhaps counterintuitive that the estimated land area can exceed the actually existing ecologically productive land area on Earth. For example, a forest logged down at twice its regeneration rate is accounted for at twice its area (Wackernagel et al. 2002). This is taken as a sign of unsustainability: 'humans are consuming resources at a rate that would require more land than actually exists' (Wackernagel and Yount 2000, p. 26). When is unsustainability apparent? In Moran et al. (2008, p. 470), the proponents of EF state as an explicit test that 'a per capita EF less than the globally available biocapacity per person' represents a minimum requirement 'for sustainable development that is globally replicable'.

6.1.1.1 Evidence

The Global Footprint Network (GFN), in partnership with the University of York in Canada, provides freely available data for almost all countries in the world and for most of these countries from 1960 to 2019, with more preliminary estimates reaching until 2022 at the time of writing this edition of the book (https://www.footprintnetwork.org/).

The global bioproductive land area is estimated at about one-quarter of the Earth's surface. According to Rees and Wackernagel (2023, p. 9), in 2022 the world's population had a total average footprint of 2.6 global hectares per capita. Set against global available biocapacity of 1.5 global hectares per capita, this is interpreted as 'the entire human enterprise was in overshoot, exceeding the planet's regenerative capacity by 70%'.

EFs have also been calculated for nations, regions and even cities (see Wackernagel and Beyers 2019). Some nations and regions, particularly the developed ones, have a much larger EF than the bioproductive land area available, and therefore an ecological deficit. However, large and sparsely populated countries can have an ecological surplus despite a large EF, as witnessed by Australia, Canada, and Russia. Not surprisingly, all city-states like Singapore and all cities examined also run such a deficit. Table 6.1 lists the consumption-based EF, the available biocapacity, and the resulting ecological deficit in 2022 of a selection of countries, as well as the world as a whole, in per capita terms. Note that a negative ecological deficit means an ecological surplus.

6.1.1.2 Critique

A whole range of methodological and other aspects of EF have encountered criticism – see, for example, van den Bergh and Verbruggen (1999), Ayres (2000), IMV (2002), Grazi et al. (2007), Fiala (2008), Best et al. (2008), Blomqvist et al. (2013), Giampietro and Saltelli (2014), van den Bergh et al. (2015), and Jóhannesson et al. (2020). On a very fundamental level, one could argue, as many critics have done, that EF adds up apples and oranges in adding such diverse items as actual land use for agricultural products and purely hypothetical land use for the absorption of carbon dioxide emissions.

Table 6.1 *Ecological footprint and deficit of selected countries and the world*

Country	EF	Biocapacity	Eco-deficit
Qatar	13.1	1.0	12.1
Luxembourg	11.0	1.2	9.7
United Arab Emirates	8.7	0.5	8.2
US	7.5	3.7	3.7
Canada	7.4	14.2	-6.8
Australia	5.8	11.0	-5.2
Russia	5.8	7.7	-1.9
Singapore	5.7	0.1	5.6
Germany	4.5	1.6	2.9
Japan	4.0	0.6	3.4
United Kingdom	3.6	1.0	2.6
China	3.6	0.8	2.8
Suriname	3.1	74.8	-71.7
World	2.6	1.5	1.1
Brazil	2.6	8.2	-5.6
India	1.0	0.3	0.7
Nigeria	0.8	0.4	0.4
Rwanda	0.6	0.2	0.3

Note: Ecological footprint (consumption-based), biocapacity and eco-deficit in global hectares per capita in 2022.
Source: https://www.footprintnetwork.org/

I will concentrate here on three main critiques. The first one addresses the way in which the EF for human-made emissions of carbon dioxide is computed. This is crucial since it is the carbon footprint, measured as the land area hypothetically required for forests to sequester all the carbon dioxide that is not otherwise absorbed by the oceans, that results in an ecological deficit at the global level and for most countries. Put differently, without the carbon footprint, which makes up around 60 per cent of the overall footprint (WWF 2022), the EF would not suggest overshoot.

One problem with the carbon footprint measure is that it is not clear what the presumed carbon sequestration rate should be. The EF methodology uses estimates of current world-average sequestration rates from primary, secondary, and plantation forests (Lin et al. 2018), revised in 2016 to take into account updated estimates presented in Mancini et al. (2016), though it does not account for uncertainty with respect to these rates (Blomqvist et al. 2013). More importantly, since the land area is hypothetical, one could hypothetically use forest types, such as eucalyptus for example, that sequester much more carbon more quickly, which would massively reduce the carbon footprint and, according to Blomqvist et al. (2013, p. 3) would no longer result in the EF exceeding the world's biocapacity. That massive afforestation with eucalyptus is not an environmentally friendly option is beside the point, since the calculation is hypothetical anyway.

Other critics, like Ayres (2000) and Blomqvist et al. (2013), argue that there are many more technical possibilities to either sequester carbon from the atmosphere than land-intensive forestry or to prevent carbon from being emitted in the first place, which would then replace the land-intensive forestry. Ayres (2000) mentions carbon capture and storage: pumping compressed carbon dioxide into empty oil and gas wells or liquefied carbon dioxide into the deep oceans. More importantly, fossil fuels could be almost entirely replaced with renewable energy, particularly wind and solar energy, in the form of electricity or green hydrogen, that is, hydrogen produced with renewable energy input. While still prohibitively costly at current costs despite massive reductions in their costs over the past few decades, the required land area would be much lower than under the forestry option, since renewable resources are far more land-efficient. Wind turbines and photovoltaic generators could even be placed on land that is not bioproductive or already in use, such as on top of buildings, or could be installed at sea or in deserts, as they often are already. Such land use would not subtract from the bioproductive land available. Of course, the economic cost at the current state of technology would be prohibitive if all of fossil fuels were hypothetically replaced with renewable energy, but given that the EF is blind to monetary valuation and therefore costs, its proponents cannot argue against considering renewable energy as a hypothetical solution to the carbon dioxide emission problem. It is also no argument against this alternative computation that the use of renewable energy on such a large scale is purely hypothetical for the time being. The same argument would apply to the forestry option employed by the proponents of EF, which is equally purely hypothetical. If the energy footprint becomes negligible, then the global EF is well within the limit of bioproductive land area available. Similarly, many developed countries no longer exhibit an ecological deficit.

The second critique is not directly targeted at EF itself but at a certain interpretation following from the concept of an ecological deficit, which is derived from EF. Whereas such a deficit would typically be regarded by economists as a normal exchange of goods and services, in which trading partners have differing comparative advantages to the mutual benefit of both partners (van den Bergh and Verbruggen 1999; van den Bergh et al. 2015), proponents of

EF see ecological deficits as inherently dangerous and undesirable, particularly at the level of nation-states. The main reason for this anti-trade bias is that 'trade reduces the most effective incentive for resource conservation in any import region, the regional population's otherwise dependence on local natural capital' (Rees and Wackernagel 1996, pp. 238ff.). As a result, a 'restoration of balance away from the present emphasis on global economic integration and interregional dependency toward enhanced ecological independence and greater intraregional self-reliance' is recommended (p. 241). Willey and Ferguson (1999, p. 2) are even more explicit in proclaiming that 'all nations should live within their own ecological capacity'. Against this, van den Bergh and Verbruggen (1999, p. 66) maintain that national boundaries are geopolitical and cultural artefacts and therefore have no environmental meaning.

As a last critique, it is doubtful whether EF really represents an indicator of SS. EF does not constrain substitutability within natural capital. This does not conflict with the first definition of SS, which refers to the value of total natural capital (except that EF is not a value measure, but a land measure). It does conflict, however, with the second definition of SS, which constrains substitutability within natural capital as well and requires maintaining critical functions of natural capital intact. Furthermore, in making total available bioproductive land area the yardstick against which hypothetical land use is measured, human activities, which are clearly not strongly sustainable, need not be indicated as unsustainable by the EF measure. Any forms of environmental pollution that are not carbon emissions are completely absent, which means that EF fails to take into account important aspects of how natural capital is degraded. Similarly, degradation or unsustainable use of natural capital on the resource or environmental amenity sides is not directly captured.

6.1.2 Material Flows: Measuring Sustainability by Weight

The concept of material flows (MF) is inspired by early work by Ayres and Kneese (1969) on industrial metabolism. Fischer-Kowalski (1998) and Fischer-Kowalski and Hüttler (1998) provide an intellectual history of material flow analysis. Its starting point is a deep dissatisfaction with environmental policies that focus mainly or even exclusively on emissions and waste products. Its proponents maintain that many environmental problems are caused long before pollutants are emitted and waste is produced because MF need to be moved in order to produce goods and services. The first law of thermodynamics is relevant here since what is extracted at some point to produce goods and services will inevitably end up in the form of dissipated heat, pollution, and waste. The argument is that it is the sheer size of MF that creates environmental problems, and this size needs to be reduced substantially to lower the pressure on the environment. Reduction of MF is suggested as a good candidate for a 'one single long-term goal in environmental policy' (Hinterberger and Wegner 1996, p. 7). The aim and policy recommendation is to reduce MF by a factor of four (Weizsäcker et al. 1997) or, more ambitiously, by a factor of ten (Schmidt-Bleek 2008), at least in developed countries, over the next 40 to 50 years.

What exactly counts as MF, and therefore becomes incorporated in MF calculations, can differ from study to study. The most comprehensive accounts provided by the UNEP, described below, distinguish between biomass, fossil fuels, metal ores, and non-metallic minerals (see CSIRO 2024 for technical details). MF can be calculated based on the production of goods and services within a country but is more commonly calculated based on the consumption of goods and services within a country. This can make a large difference for many countries with large trade volumes relative to their GDP. For example, Singapore is one of the world's largest net importers of MF at 15.7 tonnes per capita in 2020, while Australia is one of the largest net exporters at a staggering 60 tonnes per capita (UNEP 2024a, p. 31).

Higher-income countries tend to have much lower production-based MF per unit of GDP; richer countries tend to be more resource-efficient than poorer ones. Depending on how one measures GDP, the difference in resource productivity between the least developed and the most developed countries can be up to 5 (UNEP 2016, p. 26). In other words, the least developed countries require up to five times more material input for producing one unit of GDP than the most developed countries. One consequence is that as production moves from richer to poorer countries because of trade liberalisation and globalisation, the global average of resource productivity can decline. UNEP (2016) finds evidence for this from 2000 onwards as global production increasingly shifts from very material-efficient developed countries to less efficient developing ones, particularly in Asia. Viewed from the perspective of gains in production-based MF productivity over time, Wiedmann et al. (2015) show how the favourable picture of such productivity or efficiency over time in high-income countries becomes significantly weakened or disappears altogether if they look at consumption-based MF use per unit of GDP instead.

Similar to EF, the concept of MF is regarded by its proponents as an indicator in the spirit of SS (Hinterberger et al. 1997, p. 12). From their perspective, 'a core environmental condition of sustainability is a physical steady-state system, with the smallest-feasible flows of resources at the … input and output boundaries between the technosphere and the ecosphere' (Spangenberg et al. 1999, p. 492). The concept of MF, first developed by Schmidt-Bleek (1993a, 1993b), is inspired by Herman Daly (1977 [1992a]) and his emphasis on the growing scale or material throughput of the economy as the main cause of environmental degradation. It therefore shares Daly's emphasis on optimal scale and a limit to or reduction of throughput in a 'steady-state' economy as the priority for environmental policy-making. The emphasis on scale rather than efficiency also partly explains why weight is used as the unit of accounting rather than money. The other reason has to do with the perceived difficulties of monetary valuation of environmental degradation, on which more below.

From the perspective of MF, the focus needs to shift from the 'sink' side of the economy to the 'source' side. This is due to a number of reasons. First, the preoccupation with emissions and waste tends to ignore that all consumption goods (as well as services) come with a hidden 'ecological rucksack', which is defined as 'the sum of all the materials that are not physically included in the economic output under consideration, but have been necessary for production, use, recycling and disposal' (Spangenberg et al. 1999, p. 498). Substantial ecological rucksacks typically occur at the resource extraction or harvesting stage. Examples would be earth and rock displaced during non-renewable resource extraction and soil erosion in agriculture (Matthews et al. 2000, p. 1). Second, the precautionary principle is invoked to justify giving priority to a reduction of MF (Hinterberger et al. 1997). Given that uncertainty and ignorance render a precise assessment of the ecological impact of pollutants difficult and imply that many forms of environmental damage cannot be known in advance, reducing MF is seen as a promising alternative as it will reduce the pressure on the environment across the board. Third, Spangenberg et al. (1999) also argue that no environmental policy will ever be able to efficiently control the thousands of substances emitted into the environment. The monetary valuation, which is necessary for finding the efficient level of pollution, is regarded as an impossible task. In comparison, it would be much easier to control mineral and energy materials entering the economic system, the number of which is estimated between 50 and 100 in the case of Germany.

6.1.2.1 Evidence

The UNEP's International Resource Panel has compiled data, disaggregated for various subcomponents of overall MF, for practically all countries in the world over the period 1970 to, at the time of writing, 2024 (https://www.resourcepanel.org/global-material-flows-database). This is quite a remarkable achievement given that before this major data compilation effort empirical studies were relatively rare. One of the most prominent of early empirical studies is that of Adriaanse et al. (1997), which computed MF for Germany, Japan, the Netherlands, and the US over the period 1975 to 1994, which was updated to 1996 in Matthews et al. (2000) and extended to cover Austria as well. MF had also been computed for 15 EU countries by Eurostat (2002), later extended to other EU and non-EU countries, the US (Rogich et al. 2008), seven world regions (Behrens et al. 2007) and for the aggregate OECD level (OECD 2008) as well as China, Australia, and Japan (Schandl and West 2012). Wiedmann et al. (2015) provided data for most countries in the world but only for 2018.

The freely accessible UNEP database, which provides comprehensive country coverage and data from 1970 onwards, represents a real game changer.

The advantage of a global database is its comprehensive country coverage. The advantage of more focused country studies is that they allow for much more detailed analyses. For example, Matthews et al. (2000) distinguish between MF from different economic sectors as well as MF into different environmental media, namely, air, land, and water. It also allows establishing which MF remain in the economy longer than one year and which ones are dissipative and therefore difficult to recover and recycle.

At the global level, MF grew tremendously from about 30 billion tons in 1970 to an estimated 106.6 billion tons in 2024. In per capita terms, this translates into an increase from about 8.4 tons per person to about 13.2 tons per person (UNEP 2024b, p. 11). Such global averages hide very significant differences across income groups. Similar to ecological footprints where richer countries exhibit much larger footprints per capita than poorer ones, the consumption-based MF per capita of high-income countries were 24 tons in 2020, whereas they were 19 tons in upper-middle-income countries and only 5 tons in lower-middle-income countries and 4 tons in low-income countries (p. 13).

There has also been a significant change in the composition of MF away from biomass – crops, crop residues, grazed biomass, timber, and wild-caught fish – the share of which has gone down from 41 per cent to just above 25 per cent towards non-metallic minerals – sand, gravel, clay, concrete, and others – which have seen an increase from about 30 per cent to nearly 50 per cent (pp. 11–12). This tremendous rise in non-metallic minerals has been caused by major investments in man-made capital (infrastructure).

In Section 3.2.4, I discussed the rebound and backfire effects, which describe the phenomenon that improvements in energy efficiency (reductions in the energy intensity of GDP, that is, lower energy use per unit of GDP) can result in increases in total energy consumption that in part (rebound effect) or, in the worst-case scenario, in full or even more than full (backfire effect) revert and thus defeat any energy savings. The same phenomenon has been observed for MF. According to Smil (2023, p. 175), ‘relative dematerialization has been a key (and not infrequently the dominant) factor promoting often massive expansion of total material consumption’.

6.1.2.2 Critique

The most important criticism against the concept of MF is that it adds up apples and oranges (Gawel 1998, 2000; Smil 2023). From an ecological point of view, two forms of material throughput with differing environmental damage impacts cannot be meaningfully added together just because one can express both in weight terms. Without further analysis of what the material throughput consists of and what its environmental implications are, there is no reason to presume that, say, France's MF of 17.4 tons per capita in 2024 is any better than the MF of the US at 32.4 tons per capita. Indeed, one could argue that the very statement that the MF of the US was 32.4 tons per capita in 2024 is entirely void of any meaning. Similarly, it is pointless to simply rank countries according to the size of their MF per capita. Smil (2023, p. 108) agrees with this assessment: '… I am not sure what other revealing conclusions to derive from these summations of disparate input and output categories besides the obvious confirmations of substantial differences in national aggregates and in the rates of long-term growth'.

In its prescription to reduce general MF across the board, the concept seems to draw the erroneous conclusion from the difficulties of valuing environmental damage that one cannot at all successfully distinguish according to differences in environmental damage. It is simply not true that, as Hinterberger and Luks (1998, p. 7) suggest, 'in most cases it is impossible to distinguish between "good" and "bad" throughput'. In its call for general MF reduction across the board, the concept goes from a rejection of one extreme belief, namely, in the possibility of comprehensive environmental valuation, to the other extreme, which is seemingly blind towards admittedly incomplete attempts at either monetary valuation or non-monetary differentiation according to the detrimental health and other environmental impacts of different material flows. The call for general reductions in MF is not guaranteed to be ecologically effective but is guaranteed to be highly economically inefficient with respect to whatever reduction in environmental damage might be achieved (Gawel 2000). The failure to appreciate the importance of valuing benefits and opportunity costs unnecessarily renders the concept largely unattractive.

Because general reductions in MF are not guaranteed to be ecologically effective, it is also doubtful whether MF can function as an indicator of SS. Following the policy recommendation of reducing general MF by a certain factor need not reduce the stress on critical functions of natural capital if the specific MF, which are threatening these functions, are not directly addressed. Assertions such as the one made by Schandl et al. (2018, p. 835) that in order 'to reduce environmental pressures and impacts of consumption and production, high-income countries will need to substantially decrease their current per-capita material footprint' are not justified. It is perfectly conceivable that a higher per capita MF, depending on its composition, is less environmentally damaging than a lower per capita MF. Gawel (2000, pp. 165–7) is also right in arguing that proponents of MF need to be clear whether they see general MF reductions as the panacea for most if not all environmental problems, or regard differentiated MF reductions, on which more below, as a policy tool complementary to environmental policies targeting specific pollutants at the 'sink' side of the economy.

Having made this critique of general MF reductions, there is much more potential in the concept once one abandons the idea of such across-the-board reductions. For example, it is true that an environmental policy that merely focuses on the 'sink' side of the economy will tend to neglect the many environmental problems that are caused during the entire production process, and MF is to be credited with redrawing our attention to this. Furthermore, once one starts distinguishing between more and less harmful materials, then reductions in those MF, which tend to threaten critical functions of natural capital, move us towards SS.

The proponents of MF had started to take these criticisms more seriously. For example, Matthews et al. (2000, p. 3) states that 'we recognize that it is at the level of sub-accounts – the examination of specific material flows, and categories of like flows – that materials flow analysis will have most relevance to detailed policy-making'. The same document also developed a pilot study for the US, in which MF are distinguished according to their physical and chemical properties. Similarly, Hinterberger et al. (1999, pp. 364ff.) recognise a need for differentiating material flows and suggest that MF reductions need to be regarded as complementary to fine-tuned environmental policies tackling problems at the 'sink' side of the economy rather than substituting for them. However, despite a very promising early development in this respect provided by the so-called Environmentally-weighted Material Consumption (EMC) – see van der Voet et al. (2003, 2005) and Best et al. (2008), which combine MF data with environmental impact data derived from life cycle impact assessment methods – not much seems to have happened in this regard since then. Instead, there has been far too much focus on highly aggregated or even total MF analysis, which is almost useless when it comes to either measuring or advancing SS.

6.1.3 The Strong Environmental Sustainability Index

The SESI has been developed by Arkaitz Usubiaga-Liaño and Paul Ekins in a series of papers (Usubiaga-Liaño and Ekins 2021a, 2021b, 2023, 2024). It builds on much earlier work by the more senior of the two authors, Paul Ekins, together with another author, Sandrine Simon, who developed the concept of 'sustainability gaps' (Ekins and Simon 1999, 2001). Based on a firm rejection of the idea that one could reliably monetarily value natural capital depreciation, its basic idea is to measure in physical terms the gap between pre-specified environmental sustainability standards, defined as 'the maintenance of important environmental functions' (Ekins and Simon 1999, p. 39), and current violation of these standards. In the original formulation by Ekins and Simon (1999, 2001), the proposition was to translate this gap into monetary terms in the form of a monetary estimate of the costs necessary to achieve the sustainability standards.[4] For this reason, previous editions of this book discussed the concept of 'sustainability gaps' in Section 6.2 on hybrid indicators of SS, which combine physical with monetary measures. However, in the further refinement of the original idea by Usubiaga-Liaño and Ekins (2021a, 2021b, 2023, 2024), the authors now clearly refrain from bringing monetary measures into the concept, which is why the SESI is rightly discussed here in Section 6.1 on physical indicators.

The SESI is built on the SS assumption that natural capital is special and key for human well-being. Its developers distinguish between four main categories of environmental functions that natural capital provides (Usubiaga-Liaño and Ekins 2021a, p. 3):

- Source functions: these capture indicators of forestry, fishery, freshwater, and groundwater use, as well as soil erosion.
- Sink functions: these capture indicators of carbon dioxide emissions, consumption of ozone-depleting substances, the exposure of cropland and forest areas to ozone levels, the eutrophication and acidification of ecosystems, and the chemical status of surface, groundwater, and coastal water bodies.
- Life-support functions: these capture indicators of the conservation status of terrestrial habitats and the ecological status of surface and coastal water bodies.
- Human health and welfare functions: these capture indicators of outdoor and indoor air pollution, safe drinking water, water bodies and green areas for recreational use, and the conservation state of natural and mixed World Heritage Sites.

Clearly, this is a far cry from a comprehensive list of all environmental functions that matter for SS. The reason for restricting the analysis to the indicators listed above is simply pragmatic and empirically oriented based on data availability. Only those environmental functions are included for which indicators can be constructed and measured based on statistical and methodological soundness and sufficient data quality as assessed by the authors (Usubiaga-Liaño and Ekins 2021a, p. 3). Contrary to EF and MF, these indicators are not consumption-based but focus on how political units, typically countries, fare with regard to these environmental functions within their territory.

For each indicator, environmental standards are set based on the scientific literature with a view to setting a standard so that the function is 'not altered in a way that threatens its capacity to provide ecosystem services in the long-term' (p. 3). Naturally, the authors need to apply some subjective assessment with regard to what science requires in terms of SS. With the sustainability standard set, one could estimate, for each one, the gap between this standard and where a country (or, potentially, another political unit) is with respect to meeting this particular standard. However, the authors are more ambitious and want to calculate one overall aggregate index as well. This raises the following methodological issues: How is each gap normalised so they become comparable, how are they aggregated into one overall index, and what weighting of each individual component is applied to arrive at the overall index? (One can also probe the uncertainty that comes with multiple choices, an aspect that I will not pursue further here.)

In Usubiaga-Liaño and Ekins (2024), the authors explore multiple methodological choices with respect to these dimensions and the sensitivity of results to those choices. I will concentrate here on the choices originally presented in Usubiaga-Liaño and Ekins (2021a). As for normalisation, the authors opt for normalising each indicator according to the following method:

$$\text{Normalised indicator} = 100\frac{(\text{Indicator} - \text{Maximum goal post})}{(\text{Maximum goal post} - \text{Minimum goal post})}$$

Maximum and minimum goal posts need to be defined in accordance with SS standards, and the resulting normalised indicator then runs from 0 (only the minimum is reached) to 100 (the maximum is reached), with all values in between possible depending on how far a country is from the maximum goal post. In the absence of any good argument or consensus for weighting, the authors opt for equally weighting all indicators. The authors are conscious of the fact that the arithmetic mean, which produces a simple average of indicators, would open them to the charge of assuming full substitutability between each and every indicator, which is inconsistent with the second and arguably much more plausible interpretation of SS, encountered in Section 2.3.2, namely, SS understood as calling for the preservation of specific forms of natural capital that are deemed critical. Instead, they apply geometric weights such that the aggregate SESI is defined as follows:

$$\text{SESI} = \sqrt[n]{NI_1 NI_2 NI_3 \ldots NI_n}$$

where n represents the number of normalised indicators entering the overall aggregate index. Note that, contrary to the arithmetic mean, in which low performance on one normalised indicator can easily be compensated for by high performance on another normalised indicator, the geometric mean gives more weight to the indicators with low performance in aggregation to the SESI, which is more in the spirit of SS. If any of the normalised indicators are at value zero, the whole SESI collapses to zero, and very low values can significantly drag down the aggregate value. Cognisant of this, the authors opt to replace any value below 5 with the value of 5.

6.1.3.1 Evidence

Usubiaga-Liaño and Ekins (2021a) provide empirical evidence on the overall SESI and its constituent indicators for 28 European countries. According to these estimates, Finland is the frontrunner with an overall value of 60 in terms of getting closest to the maximum score of 100 on the SESI. Only three other countries score above 50, with most European countries in the range of 30 to 45. Perhaps surprisingly, Belgium comes out as the least sustainable country with a score of 19. As a group, Europe is at 47 out of 100.

While Usubiaga-Liaño and Ekins (2021a) provide a static snapshot analysis of the SESI in European countries, Usubiaga-Liaño and Ekins (2023) go beyond this and develop the measure further by adding a dynamic dimension. Labelled the strong environmental sustainability progress index (SESPI), it measures whether, under recent trends, the SS standards are likely to be met by 2030. SESPI, like SESI, is normalised to fall within a range of 0 to 100, though the meaning of the numbers is now very different. Put simply, 100 represents that the standard is met by 2030, 75 signals an improving trend that falls short of fully meeting the standard, 50 represents no progress, 25 a worsening trend, and 0 a strongly worsening trend opposite of what the required trend for meeting the standard would be. The evidence on SESPI for the 28 European countries is sobering. While performance differs from country to country, as a group, European countries only score 42 points, which suggests that on aggregate there is a slightly worsening trend rather than movement towards meeting the SS targets. With regard to the constituent indicators that together form SESPI, the highest performing one is 55, which suggests only small progress towards meeting the target.

6.1.3.2 Critique

In the concluding section of this chapter, I will praise the SESI as the most promising of all SS measures. With this in mind, there are, nevertheless, many problems and issues with this measure as well. The indicators capture a good range of SS-relevant environmental functions but are, of course, not comprehensive, typically due to data availability problems. While this is true for any measure of SS – one cannot measure something for which there are no data – other problems are specific to the SESI. On the most fundamental level, despite using geometric rather than arithmetic weights to aggregate constituent normalised indicators into the overall SESI, the method necessarily assumes that strong performance on one indicator can to some extent compensate for weak performance on another one, which is problematic at least according to one interpretation of SS.

The interpretability of the overall SESI is also limited. What does it actually mean for a country to have a score of 43 out of 100? Higher numbers, all other things being equal, are better than lower numbers. But all other things are not equal. It can well be that failing to achieve a particularly SS standard despite a relatively high performance in one indicator matters much more than failing to achieve another standard by a wider margin and therefore having a relatively low performance in this indicator. Each environmental function is distinct, and some are likely to matter much more than others, though I agree with Usubiaga-Liaño and Ekins (2021a) that there is no consensus or even near consensus that would allow a weighting of indicators. This remains a weakness of the measure.

If interpreting and acting on the overall SESI is challenging, perhaps policymakers could simply focus on each of the constituent indicators. Yet even the interpretability of each indicator is not straightforward. Typically, the indicators measure the gap between the status quo and the environmental standard in a way that does not actually measure the severity of the gap, that is, how much falling short matters. Usubiaga-Liaño and Ekins (2021a, p. 7) are perfectly aware of this shortcoming:

> For instance, the outdoor air pollution indicator represents the percentage of the population that is exposed to PM2.5 concentrations higher than the guideline values proposed by the World Health Organization. In theory, it would be possible for two countries to have the same normalised score (e.g. 75), while in the first country a quarter of the population is exposed to air pollution levels slightly above the environmental standards, while in the second a quarter of the population is exposed to air pollution levels that are several times higher than the environmental standard.

These shortcomings are more due to data availability problems, however, than inherent to the concept behind SESI itself. The SESPI, which adds an important time dimension, faces larger conceptual problems. Since it measures the trajectory from a base year towards a target year, clearly the choice of base year and the choice of target year, both of which are somewhat arbitrary, does influence quite significantly the values the SESPI takes, as Usubiaga-Liaño and Ekins (2024, p. 767) readily admit.

6.2 HYBRID INDICATORS

Hybrid approaches are those which combine physical indicators with monetary valuation. Typically, no monetary values are placed upon items of natural capital, as such. The reason is that comprehensive monetary valuation of environmental resources is regarded as impossible (Hueting 2013, pp. 85–8). Rather, only the monetary costs of achieving the standards are computed. Roefie Hueting's (1980, 1991) early pioneering work is the starting point for several hybrid approaches. However, hybrid approaches have not really taken off in the sense that initial developments from the late 1990s and early 2000s aimed at measuring SS with such hybrid indicators have not been taken up more recently. One important reason for this lack of success is the problems one encounters in empirical estimation, which I take up in Section 6.2.3. Given this lack of success, I only briefly review hybrid indicators here, starting with Hueting's pioneering work before moving to the Greened National Statistical and Modelling Procedures (GREENSTAMP) and the 'sustainable national income according to Hueting' (SNI). The concept of so-called sustainability gaps was initially also conceived as a hybrid indicator but Paul Ekins, its main proponent, has moved it away from a hybrid indicator to a physical indicator, which is why it, or rather its refinement into the SESI, is discussed in Section 6.1.3 above.

6.2.1 The Starting Point: Hueting's Pioneering Work

Hueting's point of departure is the suggestion that human impact on the environment has reached a level that threatens the integrity of environmental functions, which represents a 'new scarcity' unknown before (Hueting 1980). His proposal was to define standards, which maintain vital environmental functions intact in the spirit of SS, to estimate the costs of achieving these sustainability standards, and to subtract these costs from national income. Also subtracted should be all those expenditures which are defensive and, according to Hueting, wrongly counted as value added in the national accounts: compensatory, restorative, and preventive environmental expenditures. The resulting 'environmentally sustainable national income' (eSNI) is defined as 'the maximally attainable level of production, using the technology of the year under review, whereby the vital environmental functions (possible uses) of the not-human-made physical surroundings remain available for future generations' (Hueting and de Boer 2019, p. 21). Hueting understands his is a 'partial equilibrium and static approach' since effects on other sectors of the economy are not taken into account (Hueting 1991, p. 205).

As Hueting (1991, p. 204) points out, his proposal was provoked by the need for a practical indicator in the face of insurmountable problems of creating a theoretically correct indicator:

> In the course of a working visit to Indonesia in 1986, I was provoked by the following remark made by the Indonesian minister for Population and Environment: 'In my policy making I need an indicator in money terms for losses in environment and resources, as a counterweight to the indicator for production, namely national income. If a theoretically sound indicator is not possible, then think up one that is rather less theoretically sound.'

Hueting therefore regards his proposal as a workable, if second-best, alternative to the theoretically correct, but in his view practically impossible, valuation of environmental functions with the help of shadow prices.[5] Importantly, the eSNI is not meant to replace traditional national income (NI) measures such as GDP. Instead, 'proper judgement requires that both NI and eSNI are looked at jointly, alongside each other' (Hueting and de Boer 2019, p. 21). In Tinbergen and Hueting (1991), a rough estimate of eSNI for the world as a whole based on a large number of simplifying assumptions was given at 50 per cent of global income. As shown further below, this is the same ballpark estimate that Gerlagh et al. (2002), Hofkes et al. (2002), Hofkes et al. (2004), and Dellink and Hofkes (2008) arrive at for the Netherlands.

6.2.2 Greened National Statistical and Modelling Procedures

The GREENSTAMP are the result of a research project financed by the European Community. Proponents of GREENSTAMP want to estimate, with the help of multi-sector national economic input-output models, what the feasible economic output would be if pre-specified environmental standards were to be achieved. In specifying environmental standards, which must be obeyed, GREENSTAMP is also an indicator of SS. In estimating the opportunity costs of obeying these standards, the approach is inspired by Hueting. However, its proponents deviate from Hueting's original proposal to deduct the costs of achieving the environmental standards from actual national income. They believe that such an approach would estimate a 'sustainable income' that 'is probably lower than the national income that could be obtained, and maintained durably, while respecting the norms' (Brouwer et al. 1999, pp. 15ff.). Since achieving the pre-specified environmental standards would imply non-marginal changes, for which the partial equilibrium framework becomes untenable, general equilibrium modelling is the preferred alternative. According to GREENSTAMP proponents, the hypothetical national income that could be obtained while obeying the norms can therefore only be estimated if the feasible economic output itself is subject to modelling (O'Connor and Ryan 1999).

The GREENSTAMP methodology has been empirically tested with the help of the so-called M3ED (Modèle Economie Energie Environnement Développement) multi-sectoral dynamic simulation model. Model runs have been undertaken, among others, for France (O'Connor and Ryan 1999) and the Czech Republic (Kolar and O'Connor 2000). One of the advantages of the modelling approach is that the model can be run with different assumptions about the environmental standards. The modelling is explicitly dynamic and future-oriented (*ex ante* approach). Modelling the transition to the specified environmental standards forms an important part of the analysis. The feasible economic output is therefore estimated over a period of time and projected into the future, which can be done with appropriate assumptions about future values.

Accepting that any environmental standards set or assumptions taken about the future are always subjective, GREENSTAMP is defended by its proponents as a valuable exercise to better understand the conditions of achieving sustainability, however defined: ‘The information of most value is not found in the aggregate figures themselves – which are always open to alteration through changing assumptions – but in the richness of information and understanding obtained through construction and comparison of the different model outputs and scenarios’ (O’Connor and Ryan 1999, p. 130). The model runs for France, for example, have been undertaken for four distinct scenarios ranging from very pessimistic to very optimistic assumptions about technological advances and from very lenient to very stringent environmental standards.

6.2.3 ‘Sustainable National Income According to Hueting’

The calculations of a ‘sustainable national income according to Hueting’ (SNI) for the Netherlands, undertaken by a group of researchers at the Free University Amsterdam and Wageningen University, also build on Hueting’s work, which is very explicitly acknowledged. Like GREENSTAMP, the proponents of SNI realise that the adjustments to national income following the observance of externally imposed environmental standards can only be undertaken in a general equilibrium framework.

Contrary to GREENSTAMP’s dynamic and future- as well as transition-oriented input-output modelling approach, the SNI explicitly follows a static comparative or *ex post* computable general equilibrium modelling approach. It is defined as ‘the situation of the economy after an instantaneous change towards sustainable resource use’ (Gerlagh et al. 2001, p. 3). The aim is to establish what the income for a given year would have been if the economy had had to obey the environmental standards. Transition dynamics do not matter as two static situations are compared with each other: once before and once after the sustainability standards are imposed upon economic activity. This follows from a desire that ‘the SNI calculations should not be burdened with transition costs’ (Gerlagh et al. 2001, p. 3).

In the process of calculation, a range of simplifying assumptions are made (Gerlagh et al. 2001, 2002). For example:

- As already mentioned, all transition or adaptation costs are ignored as ‘in a way of speaking, it is assumed that the change to a sustainable economy is foreseen in advance, long enough that economic agents can integrate this transition in the planning of their investment decisions' (Gerlagh et al. 2002, p. 164).

- Abatement costs are assumed to be the same for all sectors as no sector-specific data are available.
- 'Defensive expenditures', that is, expenditures whose aim is environmental restoration, prevention of environmental degradation, or compensation for such degradation, are subtracted from national income if they enter the national accounts as value added. This follows from the consideration that actual and potential expenditures to reach the specified sustainability standards are essentially substitutes.
- Costs for remedying environmental problems, which have accumulated over a long time, are also distributed over a long time period instead of being attributed to one year only.
- The labour supply is supposed to be inelastic and the labour market clears through an adjusting wage rate, thus ensuring employment neutrality.
- The income and price elasticities of various goods need to be specified.
- The trade balance is assumed to be equal to the national savings balance, which is, in turn, assumed to constitute a constant share of national income.
- With respect to price changes in world markets, two variants are calculated: one in which prices on the world market do not change, whereas in the other, price changes on the world market are presumed to be proportional to price changes in the Netherlands.
- Similarly, because prices will change following the imposition of environmental standards, the SNI can be compared with national income either based on the initial prices or on the new prices. Together with the two scenarios about price changes on the world market, this creates a total of four variants for the general equilibrium model.

Gerlagh et al. (2002) calculate different variants of a Dutch SNI for the year 1990 in an applied general equilibrium model with 27 production sectors. Nine environmental themes are covered: climate change, ozone depletion, acidification, eutrophication, particulate matter and volatile organic compound emissions, heavy metal dispersion into water, dehydration of land, and soil contamination. The specific themes chosen are somewhat reflective of the specific environmental problems faced by the Netherlands. For all these themes, environmental sustainability standards are set such that emissions stay within the natural regenerative capacity of the environment. For the last two themes, this rule translates into a standard of zero dehydration and zero soil contamination. Then, abatement cost data based on currently available technologies are collected to estimate the costs of reaching the specified standards. Abatement costs consist of operation and maintenance costs for technical abatement measures in the first place, and value added from output losses otherwise, where these technical measures have been exhausted and output reductions are the only way left to reduce emissions.

In their calculations, Gerlagh et al. (2002) find that the costs of reducing greenhouse gas emissions represent the highest share of the costs of achieving the sustainability standards. They estimate that to reach less than 70 per cent of the sustainability standards is relatively cheap, reducing national income only by about 10 per cent. Further improvements quickly become very expensive, however. Whereas the conventional net national income is estimated at about 450 billion guilders, the SNI, that is, the income where 100 per cent of the sustainability standards are obeyed, is calculated at about 250 billion guilders.

In Hofkes et al. (2002), the calculations are repeated for the year 1995 and a comparison is drawn to the calculations for 1990. They find that 'SNI improves substantially from 1990 to 1995. Growth rates in sustainable income levels exceed growth rates in national income. … Over the period 1990–95 an absolute delinking of economic growth and environmental pressure has taken place' (Hofkes et al. 2002, p. 21). Hofkes et al. (2004) provide a trend analysis of SNI for the Netherlands over the period 1990 to 2000, while Dellink and Hofkes (2008) extend this to 2005.

6.2.4 Critical Assessment

Hueting's original proposal suffers from its partial equilibrium approach for establishing the cost curves. The costs for the implementation of each measure are estimated under the 'all other things equal' or *ceteris paribus* assumption. However, if all those measures that are necessary to achieve the sustainability standards were effectively undertaken, then the *ceteris paribus* assumption would become fictitious. The relative prices of consumption goods and input factors would change, as would the extent and structure of environmental degradation. Economic restructuring, feedbacks, and interlinkages would have to be considered in a total equilibrium analysis of the economy. This task can only be achieved with comprehensive modelling as undertaken by the other two hybrid indicators.

With respect to GREENSTAMP and SNI, the modelling approach is their chief advantage as it avoids the implausible partial equilibrium assumptions. At the same time, the hypothetical character of the estimated feasible economic output as the result of a modelling exercise also represents the greatest weakness of these indicators. The results and indeed the whole modelling exercise are difficult to understand by non-experts. Moreover, the model dependency of the estimates means that the results crucially depend on the underlying assumptions taken. The section on the SNI has illustrated this point by listing a number of assumptions needed, all of which are contestable, of course.

With hybrid indicators, one needs to be careful in interpreting the estimated feasible economic output. A great difference between actual and estimated feasible output or between national income and the estimated SNI can mean either of two things. It can either mean that the actual economy is far away from the sustainability norms or that the economy is close to fulfilling the norms, but doing so would be very costly. The environmental implications can therefore be quite different for the same monetary value. Similarly, a given difference between actual and estimated feasible output or between national income and SNI does not tell us anything about the relative achievement of SS with respect to different norms. It could be that certain norms are drastically violated while others are almost achieved, or it could be that the economy is equally far from achieving all norms. Also, a closing of the gap between actual and feasible economic output or between national income and the SNI tells us nothing about the state of the environment itself. This is because this could be *either* the consequence of the economy moving closer to fulfilling the sustainability standards *or* the consequence of a lowering of costs for achieving the standards due to, for example, technical progress. Detailed knowledge of the sustainability norms and the economy's distance from these norms is therefore essential, and one should never rely on the aggregate monetary calculations alone.

6.3 CONCLUSION

In this chapter, I have analysed attempts at measuring SS with one single overall measure. A fundamental distinction can be drawn between those who propose measuring SS with physical indicators and those seeking a hybrid between physical indicators and monetary measurement.

I have explained how the overshoot of the EF beyond the bioproductive land area available crucially depends on its method of translating carbon dioxide emissions into land area. However, the land area required to hypothetically absorb carbon dioxide emissions can be much reduced if renewable energy production is taken as the hypothetical option rather than reforestation. Doing so would then suggest that the global EF is well within the global bioproductive land area available, even though carbon dioxide emissions would still be clearly beyond the natural regenerative capacity of the global atmosphere, which violates the SS requirement. Even with the reforestation option, the fact that a global ecological deficit exists and EF therefore indicates a violation of SS is purely coincidental. This is because if only there were more bioproductive land area available globally or ecologically problematic but fast-growing and highly carbon-absorbing trees such as eucalyptus were hypothetically used on available bioproductive land area, then according to current EF methodology, the world as a whole need not have an ecological deficit. Global human impact would still be in violation of SS, however, given increasing temperatures resulting in climate change caused by excessive carbon and other greenhouse gas emissions, even though this would not be so indicated by EF.

As a matter of fact, carbon dioxide emissions are well beyond the natural absorptive capacity of the atmosphere and are still on the rise. This cannot be strongly sustainable as it will damage and in some cases irreversibly change or even destroy the natural functions of the global atmosphere. But we have known this already for many years, and we do not need EF to tell us what we have known already with what is arguably the result of a complex methodological artefact. Outspoken critics of the concept maintain that due to methodological flaws, EF does not have 'any value for policy evaluation or planning purposes' (Ayres 2000, p. 349), is 'unsuitable as a tool for informing policymaking' (van den Bergh and Verbruggen 1999, p. 71) and 'are so misleading as to preclude their use in any serious science or policy context' (Blomqvist et al. 2013, p. 1). So long as the methodology for computing the land area necessary to bring carbon dioxide emissions within the natural absorptive capacity is unchanged, I have to agree with this judgement.

Proponents of the concept of MF are correct in pointing out the misery of an environmental policy that is obsessed with emissions and waste and ignores the environmental damage created along the whole process of production of goods and services. Also, there is some fundamental truth in the statement that 'unless economic growth can be dramatically decoupled from resource use and waste generation, environmental pressures will increase rapidly' (Matthews et al. 2000, p. v). However, there are certainly more effective and more efficient ways to achieve SS than to reduce MF across the board by a factor of ten (or four or twenty or whatever, for that matter). When material flows are differentiated according to their threat to critical functions of natural capital, then the comprehensive coverage of potential environmental impacts 'from cradle to grave' has much to offer. Too little has been achieved in this respect since MF as a concept was created and developed in the 1990s. The great potential that Hinterberger et al. (1999, p. 371) had hoped would be realised never quite materialised. Aggregating and measuring by weight MF either in total or by highly aggregated groups such as biomass, fossil fuels, metals, and non-metallic minerals makes little to no economic or environmental sense. The same applies, by implication, for recommendations to reduce MF across the board.

Of all the physical measures of SS and indeed of all SS measures, including hybrid ones, the SESI is the most promising one. The strongest aspect in its favour is that it is firmly rooted within the SS paradigm. By defining environmental standards according to SS principles and estimating the gap between these standards and where countries actually are for each environmental function considered, the concept does fundamentally measure what matters in terms of SS. Conceptually, therefore, I assess this measure to be far superior to EF or MF, which, even long before one gets to practical measurement problems, are already highly questionable on a theoretical or conceptual basis. Being benchmarked against predefined environmental standards according to SS principles also means that the SESI is conceptually superior to other measures which either measure absolute performance such as Yale University's Environmental Performance Index (https://epi.yale.edu/) or performance against politically determined and often quite vague and/or arbitrary standards such as the United Nations SDGs (https://sdgs.un.org/goals).

All hybrid approaches provide interesting information on how far an economy is from reaching pre-specified environmental standards. Problems start when monetary valuation begins. Hueting's original eSNI suffers from the untenable *ceteris paribus* clause. With large-scale abatement undertaken, quantities and prices change, which defeats the partial equilibrium assumption. Only general equilibrium modelling can overcome this problem, and both GREENSTAMP and the SNI provide interesting exercises in modelling the costs of reaching pre-specified environmental standards. However, because general equilibrium modelling is required, many assumptions need to be taken, which by necessity are contentious. As some of their proponents readily admit, hybrid indicators, 'whatever concept they engage, are highly sensitive to model calibration, specification of environmental standards, technological change and other assumptions used' (O'Connor et al. 2001, p. 16).

The SNI calculations roughly point out that to achieve SS would cost about 50 per cent of national income in the case of the Netherlands. This is a very substantial cost, which would render it extremely doubtful whether any country would be willing to incur such a cost. Fortunately, the SNI provides an upper bound estimate. This is because the comparative static SNI approach necessarily overestimates the true costs of achieving SS as it is based on current technology. SS could only be achieved over a long period of time, however, during which technology would change, making the move towards SS much cheaper.

A fundamental problem that all attempts at measuring SS with one single measure encounter is that, implicitly or explicitly, they contradict the second, and arguably much more plausible, interpretation of SS, encountered in Section 2.3.2, namely, SS understood as calling for the preservation of specific forms of natural capital that are deemed critical. For measuring SS according to this interpretation of SS, one needs separate measures or indicators for each specific critical form of natural capital, and no overall aggregate single measure is possible. This will be discussed in more detail in the next, concluding, chapter.

NOTES

1. Initially, the absorptive capacity of the oceans was not included, which sparked a lot of criticism (for example, by Ayres 2000).
2. The concept of EF also builds on earlier measures of the impact of humans on ecosystems, such as Vitousek et al.'s (1986) measure of human appropriation of so-called Net Primary Productivity (NPP) and Odum's (1996) accounting of energy flows.
3. Even from the perspective of their proponents, EF is not fully compatible with SS, however, as it does not directly require compensating future generations for past and current fossil fuel use with an alternative energy resource (Wackernagel and Silverstein 2000, p. 392).
4. In principle, this can be done as follows. First, one needs to establish the necessary measures to achieve the standards. These measures can either be in the form of reducing the output of certain goods and services whose production causes environmental degradation, or in the form of input substitution and pollution abatement in production processes, or finally in the form of direct restoration and preservation. Next, cost curves have to be established for the implementation of each measure. Then, all measures are sorted with respect to their marginal cost to arrive at an overall cost curve for achieving the sustainability standard. Hypothetically, the measure with the least cost is undertaken first, then the measure with the next highest cost, and so on. In so far as there might be practical obstacles to following this sequence of least-cost measures, the estimate for the sustainability gap is too low. Ekins and Simon warn very explicitly against the idea of subtracting the monetised sustainability gap from GNP or GDP and against an interpretation of the gap as the actual amount of money that would need to be spent to achieve sustainability: the calculation of sustainability gaps 'is very much a static, partial equilibrium calculation, representing at a moment in time the aggregation of expenditures that would need to be made to reduce the various dimensions of the physical sustainability gap to zero' (Ekins and Simon 2001, p. 20). If these expenditures were actually undertaken, however, then prices would change, which contradicts the partial equilibrium assumption.
5. The hybrid indicator approach is reminiscent of Baumol and Oates's (1971) standards-price approach in the economics of pollution control, where standards are set somewhat arbitrarily, given that the efficient level of pollution is often difficult, if not impossible, to establish.

7. Conclusions

The objective of this book is to explore the limits of the two opposing paradigms, WS and SS. The analysis is based on economic methodology since both paradigms are essentially economic in nature. In Chapter 2, development was defined as sustainable if it does not decrease the capacity to provide non-declining per capita utility for infinity. The meaning of this definition was explained, and different forms of capital were introduced as the items that together form the capacity to provide utility.

In Section 2.1, many simplifying assumptions were introduced to make the analysis in this book possible, and the insights that arise from the course of examination should be seen in the light of these assumptions. In other words, the conclusions I arrive at will not necessarily hold if other assumptions or a broader perspective are taken. To give some examples: it was clearly stated that the analysis is confined to *economic* paradigms of sustainability; the definition of SD is anthropocentric and rules out the deep ecology view that non-human entities have intrinsic value independent of human valuation; finally, for a large part of the book, *intra*-generational as opposed to *inter*-generational equity issues were ignored.

Section 2.2 discussed some ethical issues of SD. As the book takes it for granted that the current generation is committed to SD, some justification was provided that makes this commitment plausible as an ethical choice. For similar reasons, two misunderstandings about what SD requires were corrected. In Section 2.3, the paradigms of WS and SS were introduced. The fundamental divergence between the two paradigms arises from differing assumptions about the substitutability of natural capital. It was pointed out that there exist two differing interpretations of SS in the literature: one calls for maintaining natural capital in value terms, the other for preserving the physical stock of (certain forms of) natural capital. The difference matters, a point to which I will return below.

Section 2.3 stressed the importance of the differing assumptions with respect to the substitutability of natural capital using climate change as a case study. The conflict between those like William Nordhaus, who come to the conclusion that only relatively minor greenhouse gas emission abatement is warranted, and those who call for far more ambitious abatement is not merely a dispute about the right rate of discount to be employed. It was argued that the main conflict must be about whether and to what extent the expected detrimental effect of climate change on natural capital can be compensated with an increase in other forms of capital. Given the substitutability of natural capital, there is no need to lower the rate of discount, from which more aggressive greenhouse gas emission abatement would follow. Indeed, lowering the discount rate is inefficient as it would lead to channelling scarce resources into emission abatement, which is likely to have a rate of return far inferior to other investment opportunities. This conclusion does not become invalid if current and future *intra*-generational inequalities are also taken into account. As long as the substitutability of natural capital is implicitly assumed, investment in the natural capital stock in the form of large-scale abatement of greenhouse gas emissions to minimise climate change and keep temperature rises as low as possible is likely to be inferior to investment in other forms of capital. Demanding aggressive reductions in greenhouse gas emissions can only be warranted if, to some extent at least, natural capital is regarded as non-substitutable. Understanding what matters helps to frame the discussion on climate change in a way that makes clear where the real conflict lies.

Chapter 3 addressed the two opposing paradigms of WS and SS in detail. The question of substitutability of natural capital as an input into the production of consumption goods was analysed first. It was suggested that the resource optimism of WS can be summarised in four propositions that were then critically assessed one after the other. Second came the question of the substitutability of natural capital as a direct provider of utility. It was discussed whether future generations can be compensated for long-term environmental degradation. Finally, the analysis addressed the link between economic growth and environmental degradation. This question had to be addressed because, in Section 2.3, the proposition that economic growth will be beneficial to the environment in the long run was taken as the main proposition of WS, so that this paradigm has to rely less on the assumption that natural capital is substitutable as a direct provider of utility, which is difficult to defend.

Chapter 3 concluded that both paradigms are non-falsifiable. The two paradigms fundamentally differ in basic claims about *future* possibilities for substitution and technical progress. While the future is not completely disconnected from the past and the present in that it is contingent on past and present decisions, we are also fundamentally uncertain and ignorant about future developments. Take resource optimism as an example: it was argued that there are powerful theoretical arguments as well as strong empirical evidence up to now in favour of natural capital being substitutable as an input into production, as WS would have it. But WS holds that natural capital will be substitutable at all points of time in the future as well. In making claims about the uncertain future, substitutability really becomes an assumption and stops being a falsifiable conjecture. And there is absolutely no guarantee that the substitutability of natural capital, despite being logically conceivable and proven to have been feasible in the past, will be possible in practice or likely to occur in the future as well.

The major conclusion from Chapter 3 is an important result because of the almost dogmatic belief of the supporters of WS and SS in the basic assumptions of their paradigm. What is necessary to maintain the capacity to provide non-declining future utility is far less clear than either paradigm would want us to believe. There is, on the one hand, reason to be concerned about the substitutability of natural capital. But, on the other hand, any call for the preservation of natural capital can rest on persuasive arguments at best. This conclusion should remind us of our humility as human beings and should caution us against blindly following either paradigm of sustainability.

In no way should Chapter 3 be misinterpreted as saying that scientific research cannot inform decision-making in a society committed to SD. Chapter 4, therefore, took up the discussion where it had stopped in Chapter 3, and the whole first part of Chapter 4 was devoted to elaborating whether and why a persuasive case can be made that certain forms of natural capital are in explicit need of preservation while others are not. To do so, it was necessary to go one step beyond this abstract notion of 'natural capital' and to look at specific forms of natural capital instead. Some of the existing literature all too often does not recognise that a more disaggregated approach towards natural capital is necessary since some forms of natural capital more than others exhibit features that distinguish them from other forms of capital and are more prone to uncertainty and ignorance.

I have argued in Chapters 3 and 4 that those forms of natural capital that serve basic life-support functions for human beings, such as the global climate, the ozone layer and biodiversity are non-substitutable in their totality and that the accumulation of persistent and highly toxic pollutants should be prevented. Conversely, a persuasive case can be made that there is no need for preserving natural resources as an input into the production of consumption goods and services and, albeit less so, as a food resource. Hence, the substitutability assumption of WS is supported more strongly from the analysis with respect to natural capital as a resource input, whereas the non-substitutability assumption of SS is supported more strongly with respect to natural capital as a provider of pollution absorptive capacity and direct utility. Another consequence is that the second interpretation of SS given in Section 2.3.2 is more appropriate than the first one: if certain forms of natural capital seem to be non-substitutable, but not others, and if these non-substitutable forms of natural capital are also not substitutable with other forms of *natural* capital, then it makes much more sense to target these forms directly and demand the preservation of their physical stocks than to maintain the value of the aggregate stock of natural capital.

The precautionary principle, SMSs, and safe operating spaces within planetary boundaries were introduced and critically assessed as ways for coping with risk, uncertainty, and ignorance that are widely prevalent and complicate considerations of which forms of natural capital are critical and in need of preservation and at what cost. Some believe that one can simply ignore opportunity costs. I have argued in Chapter 4, however, that a society committed to SD should not ignore opportunity costs. In a world of scarce resources where all choices exclude alternatives, it would be unwise to neglect the opportunity costs of preserving critical forms of natural capital. Instead, critical forms of natural capital should be preserved, subject to the condition that the costs must not be 'unacceptably high'. Clearly then, in this perspective, the precautionary principle, SMSs, and safe operating spaces within planetary boundaries provide an extension and qualification to the traditional economic approach rather than a full replacement. The objective should be to reduce uncertainty and ignorance and to strengthen valuation techniques to enable better-informed decisions on preserving natural capital. But what society regards as 'unacceptably high' costs is not a scientific, but an ethical and political question. How this question is to be solved is beyond the scope of this book. Some interesting proposals range from strengthening forms of deliberative democracy (Hammond 2021) to mock referenda (Kopp and Portney 2013) and citizens' assemblies (Reuchamps et al. 2023).

Chapter 5 was devoted to an examination of whether WS can be measured. It was shown that changes in the total capital stock per capita are the theoretically correct measure of WS. Theory is one thing, practical measurement another. There are many problems with the latter, typically driven by a lack of data of sufficiently high quality. Measuring WS such as is undertaken by the World Bank (2021) faces serious problems, and these problems have to be taken seriously in interpreting practical measuring attempts and should make one cautious in deriving policy implications. Much more effort is still needed to improve the scope and quality of the data. Furthermore, one should always be aware that any practical measure is likely to be partial in the sense that it cannot encompass every form of capital. For example, it is most doubtful whether one can measure changes in social capital with comparable validity and reliability as changes in other forms of capital.[1]

Given severe problems with providing a comprehensive practical measure of WS, maybe one must be more modest with respect to what can and what cannot be measured. It is worth quoting El Serafy (1993, p. 248) at some length here:

> I submit that we will never be able to make a complete list of the *physical* stock of natural resources existent at any point of time, let alone attach a *money value* to them in order that we might capture the annual changes of such a value in the

> flow accounts. Any pretense that we shall be able to do so shortly or even, I assert, eventually, should be dismissed as wishful thinking. What is feasible in this area is to identify in individual country situations those aspects of measurable environmental degradation that are of the most importance, and be content with adjusting the conventional accounts, particularly *income*, to reflect such partial degradation.

There is certainly a clear rationale for natural resource accounting as the stock of marketable resources for many developing countries is a very significant part of their national portfolio, and information about which share of the resource receipts should be counted as proper income and which should be counted as capital consumption is extremely important for them. This holds especially true if the government leases the exploitation of its resources to a private firm and wants to calculate resource royalties and taxes. As many natural resources are commercially marketed, prices can be established, and it is not all that difficult to keep track of changes in their stocks. Without resource accounting, what happens is that the receipts of resource depletion are fully counted as income and no correction is made for the capital loss. This makes little economic sense. A country living off its natural resource endowment might enjoy high 'income' today but will be impoverished as soon as the stock is exhausted. This runs counter to the very idea of sustainability as capital consumption is a 'sure recipe for future economic decline' (El Serafy 1989, p. 10).

Despite all practical difficulties in measuring WS as the monetary value of changes in the total capital stock per capita, I find it hard to quibble with the basic message that all income groups, all aggregate regions, and almost all countries in the world are weakly sustainable. It is hard to see how investments in produced (man-made) and human capital are insufficient to compensate for the depreciation of natural capital if, and that is the crucial issue, the substitutability assumption of WS holds. Put differently, the verdict that the vast majority of countries are on a sustainable trajectory is probably correct if, but only if, the substitutability assumption of WS is correct. The verdict is fundamentally misleading however, if the substitutability assumption does not hold.

In Section 5.2, many of the existing ISEW/GPI studies, particularly the early and pioneering ones, were found wanting as an indicator of WS because of methodological problems. This should not be misinterpreted as a defence of GDP/GNP in terms of a welfare indicator. GDP/GNP does not and should not measure welfare. Instead, it fulfils quite well the function it was supposed to accomplish when it was established after the Second World War: to provide an indicator for macroeconomic stabilisation policy of the economic activity in a country, that is, an indicator of the total output produced by the economy.[2] The Commission of the European Communities–Eurostat (1993, p. 41) states this with unambiguous clarity: 'Neither gross nor net domestic product is a measure of welfare. Domestic product is an indicator of overall production activity.' And 'total welfare could fall even though GDP could increase in volume terms' (p. 14).[3] Carson and Young (1994, p. 112) – then director and chief statistician, respectively, of the Bureau of Economic Analysis of the US Department of Commerce – are right in arguing that 'the factors determining welfare cannot be reduced and combined into a single measure that would command widespread agreement and acceptance. In this respect, a measure of welfare differs from the GNP.' I have to admit, however, that I doubt whether one could succeed in preventing policymakers, the media, and the general public from misusing GDP/GNP as a welfare indicator. Unfortunately, the welfare misinterpretation of GDP/GNP has become absolute folklore and a commonplace.

As concerns SS, Chapter 6 analysed some physical, as well as hybrid, indicators. In accordance with the major thrust of this book, which is to explore the limits of the two opposing paradigms of sustainability, my analysis has been fairly critical. That is not to say that these indicators have nothing interesting to say. For example, ecological footprints and material flows remind us that the environmental impact of the goods and services we consume goes far beyond what is contained in them or directly observable from their use. The hybrid indicators such as GREENSTAMP and SNI induce us to think about which environmental standards we would want to impose on economic activity and to calculate an approximate estimate of their opportunity costs. However, the SESI is the most promising of physical indicators but also of any of the indicators of SS. With its concept of measuring the distance or gap between actual reality and environmental standards that are predefined with a view towards respecting SS principles, it is the theoretically most promising of all measures.

Doubts and concerns remain with respect to the validity and usefulness of the indicators. Ecological footprints essentially tell us that carbon emissions are far in excess of the natural absorptive capacity of the atmosphere, which violates SS, but we knew this all along and no new complicated measure is needed to re-establish old knowledge. Material flows would be most useful if they were differentiated according to their threat to critical functions of natural capital, which is not currently done. Simply summing up flows by weight leads to one overall indicator that is both difficult to interpret and essentially meaningless. The SESI is strongest if one looks at each of its constituent component indicators separately. The aggregation into one single overall SESI, tempting though this is, remains highly problematic, a fundamental issue to which I return in the next paragraph. Hybrid indicators suffer from the difficulties of estimating in a partial equilibrium, *ceteris paribus* framework the costs of reaching predefined environmental standards, when actually reaching these standards would violate the *ceteris paribus* assumptions. The costs can therefore only be established in a general equilibrium modelling framework.

Yet, general equilibrium modelling is notoriously challenging, and results are strongly dependent on modelling assumptions.

There is a more fundamental problem with all these single overall measures of SS, however: SS understood as preserving specified critical forms of natural capital requires separate measures for each critical form. These separate measures defy aggregation into one overall measure or indicator. One would need, to list some, separate indicators tracking the loss of biodiversity and the protection of ecosystems, the emission of greenhouse gases and toxic pollutants, and the extent of over-fishing, soil erosion, and freshwater depletion. Some of these are more easily monitored and measured than others, and they need to be measured at various geographical scales. But the idea of one single overall measure of SS is misleading and unhelpful in the quest for SS. True, policymakers and the media both like one overall single figure that purportedly tells us how we fare. But since such a figure would be misleading or insufficiently informative, there is no escaping the need for more complex, separate individual indicators for various critical forms of natural capital.

Overall, readers might have the impression that many of the conclusions in this book are somewhat pessimistic. One should keep in mind, however, that the analysis here is deliberately biased towards exploring the limits of the two opposing paradigms. Exploring the prospects of both paradigms would likely lead to many insights that give rise to more hope with respect to SD. This is beyond the scope of the analysis here, however.

NOTES

1. The same applies to a potentially further form of capital, namely, cultural capital, suggested by Berkes and Folke (1992, 1994).
2. It does so rather imperfectly in developing countries where, often, much of the economic activity in the so-called informal sectors is not taken into account. Also, mainly only marketed economic activity is included since domestic and personal services produced and consumed by members of the same household or provided without payment are omitted. In addition, economic activity in the black market is, by its very nature, not included in GNP/GDP.
3. However, Daly's (1996, p. 112) claim that GNP/GDP bears no closer relation to welfare than the stock of gold bullion did in the age of mercantilism is vastly overdrawn. As Beckerman (1995, pp. 108ff.) rightly retorts: if this were true, why do people almost always migrate towards countries with a higher GNP/GDP and rarely vice versa? Also, GNP/GDP is highly correlated with basic indicators of the quality of life, such as life expectancy, infant mortality, adult literacy, and indices of political and civil rights. However, there is convergence in living standards across countries over time (Neumayer 2003b), whereas it is at least questionable whether there is convergence in per capita income (Cole and Neumayer 2003).

Appendix 1: how present-value maximisation can lead to extinction

Here is an example that shows how applying present-value maximisation with a constant discount rate as a decision criterion can lead to utmost unsustainability. Imagine that there are two utility paths available. The first one provides an infinite stream of utility at a constant level U_1. The second one provides a stream of utility at a constant level U_2. Assume that U_2 is higher than $U_1 (U_2 > U_1)$, but that the second path provides higher utility U_2 only for a finite time $T (T < \infty)$ and utility falls to zero forever after time T. Imagine that there is a social planner who must choose either of the two paths. The present value of each utility path, using a constant discount rate r, is

$$PV_1 = \int_0^{\infty} U_1 e^{-rt} dt$$

$$PV_2 = \int_0^{T} U_2 e^{-rt} dt$$

If the social planner applies present-value maximisation as the decision criterion, he or she will prefer path 2 to path 1 if and only if

$$\int_0^{T} U_2 e^{-rt} dt > \int_0^{\infty} U_1 e^{-rt} dt$$

$$\Leftrightarrow$$

$$\left[-\frac{U_2}{r} e^{-rt} \right]_0^T > \frac{U_1}{r}$$

$$\Leftrightarrow$$

$$-U_2 \left[e^{-rt} - 1 \right] > U_1$$

$$\Leftrightarrow$$

$$e^{-rT} < \frac{U_2 - U_1}{U_2}$$

$$\Leftrightarrow$$

$$r > \frac{\ln(U_2) - \ln(U_2 - U_1)}{T}$$

How is this result to be interpreted? Assume U_2 to be 10 per cent higher than U_1 and T to be 50 years.[1] Then r must be just about 4.8 per cent per annum in order to choose utility path 2, that is, to prefer human extinction in 50 years' time for the sake of 10 per cent higher utility over the 50 years to an infinite, albeit lower, utility stream! That is, present-value maximisation can lead to utmost unsustainability. This might appear counterintuitive to the reader but is a compelling consequence of the logic of discounting which gives negligible weight to the distant future. Note, however, that this result depends on the discount rate being constant throughout. If the discount rate varies with the welfare level of the future (see the discussion of the Ramsey formula in Appendix 2), then present-value maximisation need not lead to unsustainability. Clearly, the example is not realistic. No policy maker in his or her right mind would choose U_2 over U_1. Its purpose is merely to illustrate how an automatic and blind application of a constant discount rate can suggest that extinction is optimal.

NOTE

1. Because U_2 and U_1 enter the formula only in the form of arguments of an ln function, I do not have to specify them further. Any numbers that obey the assumption that U_2 is 10 per cent higher than U_1 will give the same results.

Appendix 2: the Hotelling rule and Ramsey rule in a simple general equilibrium model

In a general equilibrium dynamic optimisation context, it no longer makes sense to ask how a representative resource-extracting and resource-harvesting firm would maximise its profits, as in Section 3.2.2, p. 59, since this is only the partial equilibrium approach. Instead, here the question is how a 'social planner' would maximise social utility over infinite time.[1]

Let utility be derived from consumption only and let production be dependent on man-made capital and renewable and non-renewable resources only. There is no disembodied technical progress, that is, no technical progress that is not embodied in man-made capital. Labour input is assumed to be constant and is therefore suppressed in the production function. This is the simplest setting possible to derive the two rules.

The problem of the social planner is as follows:

$$Max \int_0^\infty U(C) e^{-\rho t} dt$$

$$s.t.\ \dot{S} = -R$$

$$\dot{Z} = a(Z) - E$$

$$\dot{K} = F(K, R, E) - C - f(R) - h(E)$$

where U is utility, C is consumption, ρ is society's pure rate of time preference, t is a time index, S is the stock of non-renewable resources, R is resource depletion, Z is the stock of renewable resources, $a(.)$ is the natural growth function of the renewable resource, E is resource harvesting, K is the stock of man-made capital, $F(.)$ is the production function, $f(.)$ is the expenditure function for non-renewable resource extraction, $h(.)$ is the expenditure function for renewable resource harvesting. $\dot{K}$ is investment in man-made capital net of depreciation. It is common to assume that renewable resources follow a logistic growth path, in which the growth rate rises with the stock of the resources initially ($a_z > 0$ for $Z < Z'$) but falls eventually after the stock has reached a certain size Z' ($a_z > 0$ for $Z < Z'$). A dot above a variable indicates its derivative with respect to time.

The so-called 'current value Hamiltonian' of this maximisation problem is

$$H = U(C) + \lambda\left[F(K,R,E) - C - f(R) - h(E)\right] - \mu R + \varphi\left[a(Z) - E\right]$$

Its optimal solution is characterised by the following set of 'canonical equations':[2]

i. Static first-order conditions

$$\frac{\partial H}{\partial C} = 0 \Rightarrow U_C = \lambda \tag{A2.i.1}$$

$$\frac{\partial H}{\partial R} = 0 \Rightarrow \lambda\left[F_R - f_R\right] = \mu \tag{A2.i.2}$$

$$\frac{\partial H}{\partial E} = 0 \Rightarrow \lambda\left[F_E - f_E\right] = \varphi \tag{A2.i.3}$$

ii. Dynamic first-order conditions

$$\dot{\lambda} = \rho\lambda(t) - \frac{\partial H}{\partial K} \Rightarrow \dot{\lambda} = \rho\lambda - \lambda F_K \tag{A2.ii.1}$$

$$\dot{\mu} = \rho\mu(t) - \frac{\partial H}{\partial S} \Rightarrow \dot{\mu} = \rho\mu \tag{A2.ii.2}$$

$$\dot{\varphi} = \rho\varphi(t) - \frac{\partial H}{\partial Z} \Rightarrow \dot{\varphi} = \rho\varphi - \varphi a_Z \tag{A2.ii.3}$$

Plugging (A2.i.2) into (A2.ii.2) and rearranging gives

$$\frac{\dot{\overline{(F_R - f_R)}}}{(F_R - f_R)} = \rho \; or \; \frac{\dot{\lambda}}{\lambda}\frac{\dot{\overline{(F_R - f_R)}}}{(F_R - f_R)} = \rho \qquad \text{(A2.1)}$$

Similarly, plugging (A2.i.3) into (A2.ii.3) and rearranging gives

$$\frac{\dot{\overline{\lambda(F_E - h_E)}}}{\lambda(F_E - h_E)} + a_Z = \rho \; or \; \frac{\dot{\lambda}}{\lambda} + \frac{\dot{\overline{(F_E - h_E)}}}{(F_E - h_E)} + a_Z = \rho \qquad \text{(A2.2)}$$

Rearranging (A2.ii.1) gives

$$\frac{\dot{\lambda}}{\lambda} + F_K = \rho \qquad \text{(A2.3)}$$

Setting (A2.1) and (A2.3) equal and noting that in a general competitive equilibrium F_K is the interest rate and F_R the price of the non-renewable resource, one arrives at the desired result that the rate at which the non-renewable resource rent is rising is equal to the interest rate

$$\frac{\dot{\overline{(F_R - f_R)}}}{(F_R - f_R)} = F_K \qquad \text{(A2.4)}$$

(Hotelling rule for non-renewable resources)

Similarly for renewable resources

$$\frac{\dot{\overline{(F_E - h_E)}}}{(F_E - h_E)} = F_K - a_Z \qquad \text{(A2.5)}$$

(Hotelling rule for renewable resources)

There is an additional term a_Z to account for the effect resource harvesting has on the stock of renewable resources and thereby on the natural growth rate of the resource. For $Z < Z'$, $a_Z > 0$, so resource rent is rising at less than the rate of interest. For that case resource harvesting has a negative effect on natural growth via reducing the renewable resource stock. For $Z > Z'$, $a_Z < 0$, so resource rent is rising at more than the rate of interest. For that case resource harvesting has a positive effect on natural growth via reducing the renewable resource stock.

If resource harvesting has a negative effect on the resource stock, the resource rent rises at less than the interest rate and therefore starts at a higher initial level. Intuitively, this is because the opportunity cost of current resource harvesting is higher than without the negative effect on the resource stock. Conversely, if resource harvesting exhibits a positive stock effect, the resource rent starts rising from a lower initial level because the opportunity cost of current resource harvesting is lower than without the positive effect on the resource stock.

I now use this model to derive another famous rule as well, the so-called Ramsey rule. Plugging (A2.i.1) in (A2.ii.1) and rearranging gives

$$F_K = \rho - \frac{\dot{U}_C}{U_C} \tag{A2.6}$$

Noting that $\dot{U}_C = U_{CC} \cdot \dot{C}$ and defining the elasticity of the marginal utility of consumption as

$$\eta(C) \equiv -\frac{U_{CC} \cdot C}{U_C} \tag{A2.7}$$

equation (A2.6) can be re-expressed as

$$F_K = \rho - \frac{U_{CC} \cdot C}{U_C} \cdot \frac{\dot{C}}{C} = \rho - \eta(C) \cdot \frac{\dot{C}}{C} \text{ (Ramsey rule)} \tag{A2.6$'$}$$

How to interpret this result? If the economy is on a dynamically optimal path, then the interest rate (the social discount rate) will be equal to the sum of the pure rate of time preference ρ and the product of the elasticity of the marginal utility of consumption η(C) and the growth rate of consumption $\dot{C}/C$.

Setting the pure rate of time preference equal to zero and looking at equation (A2.6′) again reveals why discounting, properly undertaken, has some desirable ethical properties as well, as was claimed in Section 2.1: future streams of consumption should be discounted if future generations enjoy higher consumption ($\dot{C}/C > 0$), which is ethically desirable from a sustainability point of view because if later generations are ‘richer’ than the present generation anyway, then benefits accruing to the distant future should count less than benefits accruing to the present. (Implicitly, diminishing marginal utility ($U_C > 0$, $U_{CC} < 0$) is assumed.)

NOTES

1. The same outcome would be achieved by a decentralised inter-temporal perfect competitive equilibrium (Barro and Sala-i-Martin 1995, pp. 60–71).
2. To keep the exposition as simple as possible, all initial and boundary conditions are suppressed, as are the equations of motion. All functions are assumed to be well behaved, so the first-order conditions are necessary and sufficient for an optimum.

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