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Larissa Talmon-Gros

Development Patterns of Material Productivity

Convergence or Divergence?

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In loving memory and with deep gratitude to my grandmother.

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Variables

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Section 4.1.2

Y	Output
L	Labour
A	Productivity parameter
x	Input of the intermediate product
α	Production function—share in aggregate capital stock
p	Price of a good
Π	Profit
π	Productivity adjusted profit
μ	Innovator’s probability of success
φ	Function parameter
n	Productivity adjusted research expenditure
R	Research expenditure
$\tilde{n}(\mu)$	Productivity adjusted research cost
η	Parameter
Ψ	Parameter
g	Growth rate of the world technology frontier
a	Proximity to the technological frontier
γ	Size of innovations
K	Capital
κ	Capital stock per effective worker

Section 4.2.1

y	Per capita income
$\eta_{i,0}$	Initial conditions
$\mu(\cdot)$	Probability measure

Section 4.2.2

β	Convergence/regression coefficient
γ_i	Growth rate of output per worker
g_i	Growth rate of labour-augmenting technological progress
Y	Per capita income
$y_{i,t}^E$	Output per efficiency unit of labour input
$y_{i,\infty}^E$	Steady-state value of $y_{i,t}^E$
A	Efficiency level of each worker
λ	Rate of convergence
α	Steady-state share of capital in income
n	Population growth
δ	Depreciation
ε	Error term
X_i	Explanatory variables implied by the Solow model
Z_i	Explanatory variables other than implied by the Solow model
ψ	Parameter
ξ	Parameter
s	Saving rate
q	Outcome variable
x	Explanatory variable
u	Unobserved factor
β_0	Intercept
c	Unobserved random variable
o	Composite error
$\hat{y}(t)$	Actual income at time t
y^*	Steady-state income per effective worker
τ	Difference between two points in time t
ϕ	Parameter
η_t	Time fixed effect
μ_i	Country fixed effect

Sections 4.2.3 and 4.2.4

η_t	Level of information at time t
y	Per capita income
θ	Proportionality factor
a	Common trend
ω	Constant
λ	Parameters
ρ	(Unit-root) parameter
φ	Parameter
δ	Parameter
L	Lag operator
α	Parameter
μ	Parameter
ε	Error term
π	p-values of the respective test statistic
s	Standard deviation
υ	Coefficient of variation

Chapter 5

Y	Output
A	Technical change
K	Capital
L	Labour
M	Intermediate products
s_L	Revenue share of labour
s_K	Revenue share of capital
s_M	Revenue share of intermediate products

Chapter 9

s	Standard deviation
υ	Coefficient of variation
g	Average growth rate
α	Intercept
β	Regression/convergence coefficient
ε	Error term

(continued)

η_t	Time fixed effect
μ_i	Country fixed effect
ρ	Unit-root parameter
z	Fixed effect in time-series analysis

Abbreviations

ADF	Augmented Dickey–Fuller
BRICS	Brazil, Russian Federation, India, China, Republic of South Africa
CV	Coefficient of variation
DEU	Domestic extraction used
DF	Dickey–Fuller
DMC	Domestic material consumption
DMI	Direct material input
EC	European Commission
EEA	European Environment Agency
EMC	Environmentally weighted material consumption
EU	European Union
FE	Fixed effects
GDP	Gross domestic product
HDI	Human development index
IOA	Input–output analysis
IPC	Innovation possibility curve
IPS	Im, Pesaran, and Shin
MER	Market exchange rates
MF	Material flow
MFA	Material flow analysis
MP	Material productivity
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary least squares
PPP	Purchasing power parities
SD	Standard deviation
SERI	Sustainable Europe Research Institute
SFP	Single-factor productivity
TFP	Total factor productivity
TMC	Total material consumption
TMR	Total material requirement
UNEP	United Nations Environment Programme

Chapter 1
Introduction

1.1 Motivation

The earth's natural resources play a special role for mankind. Besides being an input factor for the production of goods and services, natural resources are also the very basis of life itself providing food, clothing, and shelter as well as services like clean air to breathe or water to drink. News articles commenting on supply shortages of rare earths and strategic metals as well as fear of ecosystem collapse indicate that the world's natural resource base and its use are becoming a major issue, not only in international environmental economics and policy but also for businesses and consumers [see, for instance, Stöcker (2008), Liebrich (2010), Seidler (2012), and Lee (2013)].

One of today's key elements of the debate revolves around the potential supply of resources falling short of demand. This is not a new topic of discussion for economists. As early as the eighteenth century, Thomas Malthus was concerned with the scarcity of land and the concern that in the future available arable land would not suffice to feed the population, thus resulting in poverty and famine (Malthus 1798). Although he has been proven wrong by history, interest in the topic of natural resource scarcity has not ceased.

Contemporary economists claim that scarcities in natural resources have been overcome by technical progress and free markets (Brown and Wolk 2000). However, the recent enormous increases in nominal resource prices since the early 2000s have also affected real resource prices in such a way that over the past decade between 2000 and 2010, all of the declines in resource prices of the precedent century were erased (Bleischwitz and Bringezu 2011; Dobbs et al. 2011). During the course of twentieth century, material use increased substantially. In absolute terms it increased by a factor of 8; similarly, in per capita terms material use doubled between 1900 and 2005 (Krausmann et al. 2009). Since 1980 alone, resource extraction has increased by 45 % and the expected increase in the global population as well as future economic development will further increase demand for and thus extraction of resources. Furthermore, it can also be expected

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that the costs associated with the exploitation of resources will increase as new discoveries of resource deposits become rarer, and deposits are situated in ever more remote areas. Moreover, ore grades decline continuously and environmental constraints as well as the energy necessary to extract the resources are increasing. Additionally, political tensions or open conflicts may be generated or intensified over the access to natural resources (Bleischwitz and Bringezu 2011; Carius et al. 2007).

A second key element of today's debate about natural resources is concerned with the environmental constraints that accompany their use. The increased extraction and use of materials have various profound consequences globally on income and welfare levels as well as on ecosystems and landscapes. It becomes increasingly evident that the ability of ecosystems to absorb the outputs of economic activity is limited (Millennium Ecosystem 2005). The relationship between resource use and environmental impacts is complex and many of the environmental impacts such as global warming, eutrophication, acidification, and habitat destruction are somehow linked to the extraction, use, or disposal of resources. Yet, an exact prediction of how (over)use of natural resources affects ecosystems is not yet possible, as the relationship between exploitation, use, and disposal of natural resources is complex and variant. But it is clear that more resource use leads to more environmental pressures and it can therefore be expected that overall biodiversity will continue to be diminished, the regeneration capacity and resilience of the environment will be further reduced, and consequently environmental change will increasingly affect societies (Bringezu et al. 2009a, b).

The growing realization that "business as usual" is both unwise and unsustainable, resulting in increasing costs and constraints on growth and development and problems such as water scarcity, resource bottlenecks, and air and water pollution, has led to an increase in political and economic strategies highlighting the role of the environment and an efficient use of natural resources (OECD 2011a). These include the OECD Green Growth Strategy, the European Union's Flagship Initiative for a Resource Efficient Europe, or the UNEP's report on a Green Economy. One of the main pillars of these strategies is the idea that economic growth and resource use (as well as environmental impacts) should be delinked or decoupled from each other. The basic idea of the concept of decoupling is that if resource productivity grows faster than economic output, economic development is possible with fewer resources and also consequently fewer environmental impacts. Thus, policies aim to increase resource productivity by eliminating inefficiencies in the use of natural resources, as well as by fostering innovation. Developments of the productivity and use of natural resources have received increasing attention over the last decade or so. Indicators of resource productivity have thus become central tools for measuring the state and progress of these "green" strategies and the efficiency with which natural resources are used.

The efficiency of resource use, specifically material productivity, is the concern of this dissertation. Specifically, material productivity, i.e., the efficiency with which materials are used in production and consumption, is considered. This dissertation asks if the development of material productivity displays empirical regularities following a specific, common pattern so that eventually, the levels (and growth rates) of material productivity will assimilate. This is known as convergence analysis. So far, a systematic analysis of possible empirical regularities in the development patterns of resource productivity has not been undertaken. This dissertation aims to close this research gap. An analysis of material productivity convergence can contribute to the debate about efficient resource use by unveiling possible empirical regularities, by revealing the potential for a reduction in global material use, as well as by providing information about the situation in terms of the diffusion of resource-saving technologies.

1.2 Outline

The first part of this dissertation (Chaps. 2–6) presents the theoretical basis for the analysis of convergence of material productivity. The present chapter provides an overview of the most important definitions with regard to natural resources in Sect. 1.3, before overuse, scarcity, and the debate about sustainable development are addressed in Chap. 2. There, a brief summary is given of the consequences of overuse of natural resources, and economic reasons for this overuse are presented. The most important factors like improper allocation of property rights as well as the public good characteristics of many resources and other socioeconomic factors are discussed. The substantial overuse of natural resources has led to a range of international as well as national policies concerning sustainability and resource use. In Sect. 2.2, recent sustainability and environmental policies are presented and discussed, mainly focusing on the Green Growth Strategy of the OECD. Given that innovations form a central aspect of these sustainability policies, the relationship between innovations, technological progress, and material consumption is discussed in Chap. 3.

So-called eco- or green innovations take a special role within the latest strategies; therefore, they are discussed in Sect. 3.1. Closely related to eco-innovations are the idea of induced innovations and the direction of technological change; the basic ideas underlying these two concepts are presented in Sect. 3.2.

Chapters 4 and 5 lay out the theoretical and technical basics for an analysis of material productivity convergence: Chap. 4 presents the concept of convergence of an economic variable, the theory behind it, its econometric application, as well as an overview on existing empirical evidence. The concept of convergence originates in the examination of per capita incomes and later became part of formalized models of economic growth. The most important theoretical basics on convergence in models of economic growth are presented in Sect. 4.1. In Sect. 4.2, the different econometric methods used for the analysis of material productivity convergence in this dissertation are presented and their advantages and disadvantages are discussed. Section 4.3 concludes the chapter by providing a selection of empirical contributions to the analysis of convergence, both of per capita incomes as well as of other economic variables of interest.

In Chap. 5, methods for measuring the flow of natural resources through the economic system are introduced. The second part of this chapter presents productivity measures and their construction, benefits, and shortcomings. The theoretical part of this dissertation concludes with an overview on existing studies on the development of resource use and resource productivity in Chap. 6.

In the second, empirical part of this dissertation, a convergence analysis of resource productivity is conducted. Chapter 7 presents the research question and its relevance for the current debate. In Chap. 8, the data and descriptive statistics as well as a first descriptive analysis are presented. The empirical analysis in Chap. 9 analyzes material productivity convergence explicitly. In Sect. 9.1 σ-convergence is analyzed. In Sect. 9.2, a regression analysis of β-convergence in both a cross section as well as a panel framework is conducted. Section 9.3 presents a time-series analysis of convergence of material productivity, both for the overall sample as well as for separate clubs of countries. The discussion in Chap. 10 provides a summary of the results of the previous chapters and discusses their implications as well as possible limitations with regard to the potential for a global reduction of resource consumption. The conclusion in Chap. 11 recaps the insights from the theoretical chapters and relates them to the findings of the empirical analysis.

1.3 Definitions

This chapter presents some definitions concerning natural resources with regard to their relevance for this dissertation. Natural capital is defined as “natural assets in their role of providing natural resource inputs and environmental services for economic production” (OECD 2007). Tietenberg and Lewis (2009) provide a similar definition, while Neumayer (2010) highlights the anthropocentric aspect more strongly. However, given the importance of international organizations such as the OECD for policies concerning natural resources, their definitions are preferred in the context of this dissertation.

The inputs and environmental services provided by natural capital include three principal categories: natural resource stocks, land, and ecosystems. All of them are considered to be “essential to the long-term sustainability of development for their provision of ‘functions’ to the economy, as well as to mankind outside the economy and other living beings” (OECD 2007).

Within this definition, one can identify three aspects that are of special interest in the context of this work: natural resource stocks, ecosystems, and the provisioning of “functions.” Each will be described in more detail. Firstly, natural resources are defined as

> “[N]atural assets (raw materials) occurring in nature that can be used for economic production or consumption. The naturally occurring assets that provide use benefits through the provision of raw materials and energy used in economic activity (or that may provide such benefits one day) and that are subject primarily to quantitative depletion through

> human use. They are subdivided into four categories: mineral and energy resources, soil resources, water resources and biological resources." (OECD 2007)

Within these four categories, resources can be subdivided with regard to different properties: whether it is a flow or a fund resource, regarding exhaustibility and regarding storability (Bergstrom and Randall 2010, pp. 30–34).[1]

When there is a given time with a fixed stock with given quality and quantity dimensions, one speaks of a "fund resource." An example is the carbon and oxygen cycles that build coal, crude oil, and natural gas in the ground over very long time periods. Flow resources comprise a continuous stream of resources with given quality and quantity dimensions for a given time period. They are "provided in some predetermined quantity and quality beyond human control and must be used when provided or otherwise wasted" (ibid, p. 36). Examples are wind, solar radiation, or rainfall.

Regarding the exhaustibility of resources, one can distinguish between non-exhaustible resources and exhaustible resources that are either renewable or nonrenewable. Non-exhaustible resources cannot be depleted in human time, for example, the sun, wind, tides, and geothermics (Rogall 2008, p. 58). The supply of an exhaustible, renewable resource can be renewed in a relatively short period of time. Examples include crops, forests, and wildlife populations.

An exhaustible nonrenewable resource has a supply that is depletable and cannot be replenished within a human time horizon. Mineral deposits and coal, crude oil, and natural gas are examples of exhaustible nonrenewable resources as the carbon–oxygen cycle does not occur in time frames relevant for human behavior. Within the stock of exhaustible or depletable resources, there exist three different concepts for classification (Tietenberg and Lewis 2009): current reserves, potential reserves, and the resource endowment. These concepts were originally developed by the United States Geological Survey and categorize resources according to an economic and a geological dimension. The economic dimension includes economic and subeconomic resources and the geological dimension includes identified and undiscovered resources. Current reserves are defined as those known resources "that can profitably be extracted at current prices" (ibid). Potential reserves however depend on the price of the resource. If resource prices increase higher, potential reserves become larger; for example, it becomes economical to mine lower grade ores or to use more expensive mining technology. Price developments and technological progress influence the size of current and potential reserves, and these two concepts should therefore not be considered as fixed. Resource endowment describes the total occurrence of natural resources in the crust of the earth and is not dependent on prices at all.

Storability is a concept typically applied to flow resources. Using present technology, one cannot capture and store a non-storable flow resource such as solar radiation or wind for future use. An example of a storable flow resource is

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[1] The exact distinction between the different subdivisions is also slightly varying among different authors; see, for example, Tietenberg and Lewis (2009, p. 135).

rainfall, as this can be stored in reservoirs for future use. Therefore, a flow resource is transformed into a fund resource, i.e., deposits and withdrawals can be made according to human will.

The definition of natural resources is very broad and can therefore be problematic. To overcome this, the term "material resources" has been coined (UNEP 2011b). In contrast to resources, the term "material" refers to resources that are actually used in production and consumption processes. Material resources are understood as "natural assets deliberately extracted and modified by human activity for their utility to create economic value. They can be measured both in physical units (such as tons, joules or area), and in monetary terms expressing their economic value" (UNEP 2011a, p. 2). This allows the vague concept of resources to become something that can be more easily measured. At this point, the distinction between resource and material productivity becomes relevant. Material productivity refers to the productivity of materials directly used in production and consumption processes, whereas resource productivity is a wider concept which also includes indirect contributions such as unused extraction from mining. In public debate as well as in the scientific community, the two terms are often used interchangeably even though this is conceptually not fully sound.

Secondly, the ecosystem, another part of natural capital, is defined as "a system in which the interaction between different organisms and their environment generates a cyclic interchange of materials and energy" (OECD 2007).

Bergstrom and Randall (2010, p. 13) put it slightly different, defining an ecosystem as "a community of plants, animals, and people interacting in a given physical environment with each other and the environment and operating as a unit." Terrestrial ecosystems, aquatic ecosystems, and atmospheric systems can be distinguished (OECD 2007). Within ecosystems there are two basic categories of components—biotic and abiotic—and together with their connections, they make up the structure of the ecosystem (Bergstrom and Randall 2010). Within this structure, two major ecosystem processes take place: the one-way flow of energy through the system, i.e., the movement of solar energy through the ecosystem and the cycling of chemicals in the system (carbon, oxygen, phosphorus, nitrogen, sulfur, and the hydrologic cycle). These two major processes support ecosystem functions. Those are defined as "environmental tasks performed by an ecosystem at the scale of a specific ecosystem type (e.g. forest, lake, ocean, river)" (ibid, p. 22). Examples are the natural development of wildlife or changes in the quantity or quality of soil nutrients. Overall, two major biotic and three major abiotic processes of ecosystems can be identified: the natural development of plants, wildlife, and water, air, and mineral supplies. These ecosystem processes provide ecosystem services, which are defined as "the provision of ecosystem inputs, the assimilative capacity of the environment and the provision of biodiversity" (OECD 2007). Ecosystem inputs are defined as those substances and gases that are withdrawn from the ecosystem for production and consumption purposes which to some extent overlap with natural resources as defined above.

Thirdly, the three categories of natural capital—natural resource stocks, land, and ecosystems—also provide functions to the economy, to humankind in general, and to other living beings. These functions are also called environmental functions and consist of the resource function, the sink function, and the service function of natural capital. Another expression used in this context is “ecosystem services,” for instance, by the Millennium Ecosystem Assessment (2005, p. v). In this case the authors distinguish between provisioning services, regulating services, cultural services, and supporting services. Despite semantic differences, with regard to their content, the definitions of OECD and the Millennium Ecosystem Assessment are in agreement. The OECD defines the ecosystem functions as follows: the resource function is defined as “the capacity of natural capital to provide natural resources which can be drawn into the economy to be converted into goods and services for the benefit of mankind. Examples are mineral deposits, timber from natural forests, and deep sea fish” (OECD 2007). The sink function describes the “capacity of the environment to absorb the unwanted by-products of production and consumption; exhaust gases from combustion or chemical processing, water used to clean products or people, discarded packaging and goods no longer wanted” (ibid). The service function contains the “capacity of the environment to provide the habitat for all living beings including mankind” (ibid). This includes survival functions, i.e., essential aspects of habitat such as air to breathe and water to drink as well as amenity functions, which are not essential for survival itself but improve the quality of life, e.g., by providing a pleasing landscape for leisure activities.

Overall it can be summarized that natural capital in all its different forms serves not only to provide raw materials for production and consumption but simultaneously embody the basic, essential foundation for the existence of all living organisms on earth (OECD 2001d, p. 273; OECD 2008c, p. 20; Rogall 2008, p. 59).

Part I
Theoretical Foundation and Existing Empirical Evidence

Chapter 2
Overuse, Scarcity, and the Debate About Sustainable Development

The last decades have shown that natural capital in basically all its dimensions is subject to substantial overuse. Rogall (2008, pp. 31–39) classifies overuse into five exemplary areas. They include but are not restricted to (1) climate change; (2) overuse of renewable resources; (3) use of nonrenewable resources; (4) destruction of ecosystems, species, and landscapes; and (5) threats to human health. Each of these will be briefly described[1]:

1. The consequences of a failure to prevent a global temperature increase of over 2 °C may result in a reduction of water reserves, drought, desertification, and more frequent extreme weather events. This in turn causes problems for human health, damage to ecosystems, and the extinction of species. The Intergovernmental Panel on Climate Change as well as the Stern Report estimate that mitigation costs of climate change will comprise up to 3.5 % of global GDP (IPCC 2007, p. 69; Stern 2007, p. 260).
2. Examples of renewable natural resources which are being overused beyond their regeneration rate include soil, fish, and freshwater. 66 % of cultivable land worldwide is damaged and around 11 % of all soil is degraded (BMU 2006). Similarly, around 70 % of all freshwater sources are either contaminated or degraded. Biodiversity loss due to human actions occurs 1,000 times faster than the long-run natural rate of extinction; 10–30 % of mammal, bird, and insect species are threatened by extinction (Millennium Ecosystem Assessment 2005, p. 39).[2] The Food and Agriculture Organization of the United Nations reports that in 2007 only 20 % of global fish stocks were moderately underexploited or moderately overexploited, with the remaining 80 % fully exploited, overexploited, depleted, or recovering from depletion (FAO Fisheries and Aquaculture Department 2009). The Millennium Ecosystem Assessment

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[1] For more details, see also OECD (2001c).

[2] An overview on the arguments regarding the necessity to protect biodiversity can be found, for instance, in Bergstrom and Randall (2010, pp. 380, 400–401).

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(2005) considers approximately 60 % of ecosystem services to be degraded or used in an unsustainable manner.

3. The use of nonrenewable resources: Although the market exhibited major price increases and increased volatility for raw materials like minerals and ores in the last decade, Tietenberg and Lewis (2009) argue that "for most resources we shall never run out" (ibid, p. 604). They consider the rising cost of extraction and use (including environmental cost) as the limiting factors, rather than the exhaustion of nonrenewables, and argue that "the limits of our uses of the resources are not determined by their scarcity in the crust of the earth, but rather by what we would have to sacrifice to extract and process them" (ibid). This is in accord with the reasoning that current reserves can be expanded with the help of technological progress, which can facilitate finding new sources for conventional material, uncover new uses for conventional materials, and reduce the amount of resources needed to produce the products (Tietenberg and Lewis 2009). For example, the extraction of ores and fossil fuels lowers the average quality of the deposit, as initially higher quality ores and fuels are extracted but as prices rise it also becomes profitable to mine lower grade ores. The mining of inferior deposits leads to higher pressures on the environment, as more mining waste is accumulated in these cases (see also UNEP 2011a).
4. The destruction of ecosystems, species, and landscapes relates closely to the overuse of renewable resources but focuses more on species and ecosystems that are not or cannot (yet) be used as factors of production. Important aspects include aesthetic and ethical questions with regard to the extinction of species and the destruction of ecosystems and landscapes (Rogall 2008).
5. Production and consumption processes lead to organic and inorganic pollutants being emitted into the environment which can cause a slow toxification of the biosphere due to their longevity. Ultimately they can pose threats to human health. Examples are heavy metals and environmental toxins, emissions of pollutants, noise, summer smog, or the thinning of the ozone layer (Rogall 2008).

In conclusion, there is significant evidence for the overuse of natural capital, including its sink function. In an attempt to quantify overuse beyond safe limits, Rockström et al. (2009) provide an overview of planetary boundaries for a number of earth-system processes as well as their threshold levels. They argue that these boundaries have been crossed regarding climate change, biodiversity, and the nitrogen cycle.

Reasons for the overuse and consequently possible scarcities of natural resources are diverse. The next section provides an overview of economic explanations for overuse of natural resources.

2.1 Reasons for Overuse

The market system sets a number of incentives for consumers and producers to act in the face of scarcity, as long as property rights are well defined (Tietenberg and Lewis 2009, p. 606). However, especially in the case of natural resources, property rights are often not well designed which in turn leads to the appearance of externalities [see, e.g., Bergstrom and Randall (2010), Faucheux and Noël (2001), Endres (2007), or Tietenberg and Lewis (2009)]. Additionally, many natural resources exhibit public good characteristics, which are another important factor for overuse. Whenever "many costs of using unsustainable resources are born by someone other than those making the resource choices, private and social cost will not align" (Tietenberg and Lewis 2009, p. 607) and thus the market process will not be able to function correctly.

Besides the two main reasons for the overuse of natural resources—externalities and public good characteristics—the next paragraphs also describe factors from outside the economic sphere such as social and political factors.

There exists an extensive literature on externalities and they may be the most discussed source of market failure (Bergstrom and Randall 2010, p. 192). "An externality exists whenever the welfare of some agent, either a firm or a household, depends not only on his or her activities, but also on activities under the control of some other agent" (Tietenberg and Lewis 2009, p. 71). In a regime of private property rights, the exclusivity of the benefits and costs using the resource should accrue to the owner of the resource. However, in the case of natural resources, the costs of using the resource are often borne not only by the owner but also by other agents or the public. In this case the marginal costs of production are greater for society as a whole rather than for the individual producer. This can in consequence lead to a suboptimal allocation of resources and therefore their overuse.[3]

Open-access resources on the other hand have no defined property rights; therefore, no one can legally restrict access to them. As a consequence, they can be exploited on a first-come-first-serve basis. Their main features are nonexclusivity, which means that anyone can exploit the resource, and divisibility, meaning that any withdrawal from the stock lessens the amount available for the use of others. These features also lead to inefficient allocations, as with sufficient demand open access will cause overuse and as scarcity rents cannot be appropriated by anyone, there is therefore no incentive to conserve. Well-known examples of an open-access resource are global fisheries (Tietenberg and Lewis 2009).

Another main reason for the overuse of natural resources lies in the public good characteristics that some of them display. A public good is characterized by non-excludability and indivisibility. Non-excludability refers to the fact that once a good is provided, everyone can enjoy the benefits of it, regardless of whether he or she has paid for it. One person's consumption does not lessen the consumption possibilities of other people when a good is indivisible. Examples of public goods

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[3] See, e.g., Tietenberg and Lewis (2009, p. 71) for the well-known river example.

are clean air, clean water, biological diversity, or a beautiful landscape. The special characteristics of these goods can lead to a supply that is smaller than efficient or an overuse, as existing scarcities are not reflected in the prices (Tietenberg and Lewis 2009; Bergstrom and Randall 2010; Rogall 2008).

Additionally, there are three major socioeconomic factors that facilitate the overuse of natural resources, especially in the light of open-access resources and public goods. These are the so-called *Tragedy of the Commons, the Prisoners' Dilemma, and Freeriding*. The "tragedy of the commons" refers to a situation in which it is rational for an agent to use open-access resources less carefully than he or she would have done in a regime of private ownership (Hardin 1968). The "prisoners' dilemma," a game-theory concept, refers to a situation when the rational behavior of the participants leads to a result that is explicitly bad for them. In the context of natural resources, this means that a change could only be achieved if *all* individuals altered their behavior, but as the individual cannot be sure of this, it is rational for the individual not to forego the additional utility (Rogall 2008, p. 64). "Freeriding" is a problem often found in the context of public goods and occurs because once the good is provided each person can enjoy the benefits of the good without having had to contribute to it. This in turn diminishes the incentives to supply this good which accordingly leads to an undersupply (Tietenberg and Lewis 2009; Rogall 2008).

The debate about further factors affecting overuse of natural resources includes imperfect market structures, divergence of social and private discount rates, discounting of future damages in general, government failure (rent seeking as well as the failure to ensure sustainability), population growth, economic growth, consumption patterns, psychological barriers to change, as well as poverty which leads to increased environmental pressures [see, e.g., Bergstrom and Randall (2010), Tietenberg and Lewis (2009), and Rogall (2008, pp. 64–67)].[4]

The combination of the above factors leads to a suboptimal allocation of resources and therefore substantial overuse. The European Environmental Agency considers past as well as future trends to be the result of a range of interdependent social and economic factors (European Environment Agency 2005, pp. 11–17). Notably these include demographic development, economic growth, and development patterns such as technology, economic structure, as well as production and consumption patterns. The link between demographic development and resource use is intuitive: more people in general use more resources. The United Nations World Population Prospects (2009) predicts that global population will increase by about 30 % until 2050 (assuming a medium fertility scenario). For the greatest part, this increase will take place in developing countries and emerging economies, in parts of the world where basic material needs are greatest. Therefore, material use can be expected to rise accordingly. Additionally, changing consumption patterns in emerging economies towards the "western" mode, for instance, in terms of diet,

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[4] Especially the aspects discounting of future damages and the role of economic growth play in environmental degradation are discussed extensively. See, e.g., Bergstrom and Randall (2010, Chap. 7) and Neumayer (2010) for the debate on discounting.

can be expected to further increase material use. Large disparities in income can make international cooperation more difficult and poverty often leads to a deterioration of environmental quality besides the consequences with regard to disease, malnourishment, conflicts, and migration (OECD 2001d, pp. 22–27). Generally, economic growth is expected to lead to an intensified material throughput in the economy and therefore to an increased use of resources. However, economic growth caused by technological progress or capital accumulation may also lead to efficiency improvements and therefore reduced resource inputs.[5]

The third important set of drivers for resource use patterns includes technology, structure of an economy, as well as patterns of production and consumption. The use of natural resources and their influence on the environment are substantially influenced by the form and efficiency of the dominant technologies. The extent to which resource-intensive or resource-extensive industries play a role in the economy is relevant for its structure and therefore patterns of resource use. Additionally, the stage of economic development influences resource use. It is assumed that the more industrialized a country is, the lower its resource use per unit GDP. Given these factors and their interdependencies, it is very likely that resource use will continue to intensify in the future and make existing scarcities more acute (Millennium Ecosystem Assessment 2005, p. 17).

As a consequence of the overuse of natural resources, the differences between modern and preindustrial environmental damages become more evident. Environmental problems are not longer locally restricted but have become universal; they have also become so complex that a cause can no longer be easily identified. Scientific tools have become necessary to measure the effects of environmental degradation; they can no longer be experienced through sensual experience. And the damages occurring are often irreversible damages rather than short run [Sieferle (1988) cited in Förstner (2008)]. Additionally, there is evidence that nonlinear changes in ecosystems are becoming more likely. This means that once a threshold is crossed, the state of the system is fundamentally altered. These alterations can be abrupt, large in magnitude and difficult, expensive, or even impossible to reverse. They pose severe consequences for human well-being; however, their prediction is very difficult. Examples include disease emergence, such as in the case of cholera, eutrophication and hypoxia, collapse of fisheries, species loss, and regional climate change. Loss of biodiversity lowers the level of disturbance an ecosystem can withstand without crossing a threshold and fundamentally changing its structure and functioning (called resilience). Additionally, pressures from different directions push the ecosystem more strongly above their thresholds (Millennium Ecosystem Assessment 2005, pp. 11–12).

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[5] The question whether economic growth automatically improves environmental quality is at the center in the debate about the environmental Kuznets curve. The environmental Kuznets curve postulates an inverted-U relationship between pollution and economic development. Neumayer (2010) presents an overview on economic growth and the environment as well as the environmental Kuznets curve, and Tietenberg and Lewis (2009) also discuss the Kuznets curve.

Another, though different consequence of the overuse of natural resources, is the emergence of debates concerning sustainability, sustainable development, and subsequent policies.

2.2 Sustainability, Green Growth, and Environmental Policies

Environmental problems due to the overuse of natural resource have increasingly gained public attention over the last 3–4 decades. A growing concern is whether economic development in today's form can be sustainable in the long run leading to a greater concern for the environment. As a result of this global phenomenon, the United Nations held a conference on environment and development in 1992 and agreed on the idea of sustainable development (Rogall 2008). The United Nations adopted the definition of the Brundtland Report which defined sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987, p. 8). Part of the appeal and yet at the same time the problem of the concept is that it is very vague and therefore allows a whole range of definitions. For instance, Pezzey (1992) mentions several dozen different definitions found in the literature.

Discussion since then has focused on three aspects: the definition of sustainable development or sustainability, the determination of conditions for sustainable development, and the question of whether a national or the global economy is on a sustainable development path (Pearce and Atkinson 1996).

Considering only the economic definition of sustainable development, sustainability can be defined as "non-declining per-capita human well-being over time" (Pearce and Atkinson 1996, p. 166) or as "non-decreasing capacity to provide non-declining per capita utility for infinity" seem most accepted (Neumayer 2010, p. 7). This translates into the condition that the underlying capital stock is kept constant [see, e.g., Neumayer (2010), Pearce and Atkinson (1996)].

The composition of this capital stock and the substitution possibilities between the different components gives rise to the distinction between weak sustainability and strong sustainability. Weak sustainability demands that the overall stock of capital remains the same, whereas the different forms of capital such as natural capital, human capital, and man-made capital can compensate for each other, i.e., under this rule, it is permissible to diminish natural capital if man-made capital is increased in return. Strong sustainability demands that the natural capital stock is held constant while at the same time total capital remains constant or is increasing (OECD 2001d; Pearce and Atkinson 1996).

Measures to monitor sustainability differ according to the chosen concept of sustainability. In Neumayer (2010), a discussion of several measures for weak and strong sustainability can be found.[6]

The issue of "Green Growth" (OECD 2011c) or a "Green Economy" (UNEP 2011b) has entered the international policy agenda alongside the debate about sustainable development in recent years. It is related to sustainability in such a way that over the years, the recognition has been growing that "achieving sustainability rests almost entirely on getting the economy right" (UNEP 2011b, p. 16). The United Nations Environment Programme considers the transition towards a green economy as a strategic economic policy agenda for achieving sustainable development (UNEP 2011b, p. 19). Similarly, the OECD explains that its Green Growth Strategy develops an "agenda for delivering a number of Rio's key aspirations" (OECD 2011c, p. 11). It is not to be considered as a replacement for sustainable development but as a subset of it. The concept of "Green Growth" is narrower than the concept of sustainable development, because the "Green Growth" approach focuses on economic and natural assets, whereas sustainability requires also the concern for human and social capital. Nevertheless, specific attention to social issues and equity concerns resulting in a greening of the economy is warranted and strategies concerning the broader social pillar of sustainable development should be implemented in parallel (OECD 2011c). The UNEP's concept of a green economy also caters for broader issues such as intergenerational equity and poverty eradication.

These recent approaches can thus be seen as a subset of the wider approach of sustainability. Next, the essentials of the OECD Green Growth Strategy will be briefly presented. Generally, the strategy seeks to "encourage greener behaviour by firms and consumers, facilitate smooth and just reallocation of jobs, capital and technology towards greener activities and provide adequate incentives and support to green innovations" (OECD 2011c, p. 11). Amongst others, it aims to close the gap between private and societal returns from economic activity and raising returns to "green" investment and innovation. Its implementation involves two sets of policies: the first policy set includes framework conditions which mutually enforce economic growth and the conservation of natural capital and which are supplemented by innovation policies. Possible instruments are core fiscal and regulatory measures like tax and competition policy, designed and executed to maximize the efficient allocation of resources. Innovation policies aim at rewarding the inventiveness necessary for using less natural capital in a more efficient manner. The second policy set explicitly targets efficient use of natural resources and increasing pollution costs. With regard to instruments, the OECD recommends

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[6] Measures to examine weak sustainability include Genuine Savings and the Index of Sustainable Economic Welfare (ISEW) or Genuine Progress Indicators. The most important indicators for strong sustainability are physical indicators like ecological footprints and material flows as well as hybrid indicators combining physical indicators with monetary valuation, such as the Greened National Statistical and Modelling Procedures (GREENSTAMP), the so-called sustainability gaps, and the sustainable national income according to Hueting (SNI) (Neumayer 2010).

using prices where possible in combination with other complementary policy instruments (OECD 2011b, c, pp. 12, 35–83). Practically, the use of taxes or tradable permit systems is suggested as core strategies [see also von Weizsäcker (2009)]. These instruments can be supplemented by regulation, technology-support policies, and voluntary approaches as well as information-based measures. More details on environmental policy instruments can be found in OECD (2011c) Chap. 2. Particular attention is required for innovation and overcoming inertia; OECD (2011b) discusses this as well as challenges specific to green innovation.

Progress towards "Green Growth" should be monitored by groups of indicators describing and tracking changes in several fields: These comprise the productivity in the use of environmental assets and natural resources, the economic and environmental asset base, environmental dimensions of the quality of life, and policy responses and economic opportunities. This set comprises about 25 indicators which may be used to construct a composite indicator. Alternatively, a selection of these indicators will be chosen as headline indicators (OECD 2011c). The area of environmental and resource productivity comprises of carbon and energy productivity indicators, resource productivity indicators, as well as of multifactor productivity (including environmental services).

Similarly, within the Europe 2020 strategy and the appertaining Flagship Initiative for a Resource Efficient Europe, the European Union proposes a range of policies to make Europe more resource efficient. As part of that, resource productivity has been established as the provisional lead indicator for measuring progress (European Commission 2011b).[7] This indicator is the focus of this dissertation. However, instead of the term resource productivity, the term material productivity will be used, as this is conceptually more correct. Despite its relevance for economic and environmental policy making as well as for future development scenarios, very little is known about empirical regularities or development patterns of material productivity. Moreover, the requirement to cater for and avoid the so-called rebound effect is included in all three approaches mentioned above, even though actual measures remain vague. A rebound effect occurs when efficiency gains are translated into lower prices, which increases the real income of consumers and in turn makes increased consumption possible, for instance, if more efficient heating results in warmer homes instead of lower energy use (OECD 2011c).[8]

The prominent role played by innovation and technological progress for improving resource efficiency has been recognized in the context of policy recommendations. The next chapter will discuss the relation between technological progress and innovation and material consumption in depth.

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[7] An overview over international as well as European environmental policy can be found in von Weizsäcker (2009).

[8] See, for example, Dujmovits (2010).

Chapter 3
The Relationship Between Technological Progress and Material Consumption

Technological innovation can help to realize environmental objectives at lower costs. Innovations and especially green or eco-innovations play a major role both in a more general debate about sustainability as well as in the discussion of "Green Growth" and the like [see, for instance, UNEP (2011a, b) or OECD (2011c)].

Innovations are today still largely understood as Schumpeter described them in 1934. He distinguished between five different forms of innovations and called them "new combinations." They included the production of a new product or a new product quality, the introduction of a new production method, the opening up of a new market, the conquest of a new source for resources or semifinished goods, or execution of a new form of organization, such as the creation of destruction of a monopoly (Schumpeter 1987). Today, the OECD distinguishes between product, process innovations, marketing, and organizational innovations (OECD 2005). In the context of the recent debate, the OECD highlights the importance of organizational and systemic innovations in addition to technological breakthroughs.

From a theoretical point of view, innovation on the level of an individual firm corresponds to a shift of the individual production function or, expressed more precisely, the unit isoquant shifts towards the origin. The sum of innovations could be considered as a macroeconomic interpretation of innovation, i.e., technological progress. This can either be thought of as a continuum of constantly evolving production functions or the identification of the economy with a single firm. Thus, the effect of technological progress shows theoretically as a shift of the production function. Generally, the exact definition of technological progress is difficult to grasp and depends on the purpose of the examination. Definitions range from inventions, technological change, innovations, and changes in the production function to productivity increases.[1] In the context of macroeconomic growth

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[1] Another complication of the matter arises because some authors differentiate between the terms technological and technical progress, the former referring to the advancement of technological knowledge and the latter to the progress of knowledge that is used in production, i.e., process as well as product innovations; see Walter (1969). Here, however, the two terms will be used interchangeably.

L. Talmon-Gros, *Development Patterns of Material Productivity*, Contributions to Economics, DOI 10.1007/978-3-319-02538-4_3,

analysis, technological progress can only be measured by its productivity effect (Walter 1969).

Technological progress allows the same output to be produced with fewer inputs or more output to be produced with the same inputs. It is thus one of the factors (besides the movement towards efficient points on the production function and scale effects) that can lead to an increase in productivity, which can be measured by the increase in the total factor productivity (TFP) (Walter 1983, p. 100).

By means of the growth accounting framework, first introduced by Solow (1957), an estimate for total factor productivity growth can be calculated. In this context the growth rate of an economy can be expressed as the sum of two components, namely, the rate of TFP growth, i.e., the effect of technological progress, and the rate of "capital deepening," i.e., the rate of capital accumulation. The effect of technical progress is measured indirectly by accounting for the growth of the observable inputs and comparing it to GDP growth. The residual between this is considered the growth rate of technical progress or TFP growth. Thus, GDP growth can be deconstructed into components associated with factor accumulation and technological progress with each weighted by their respective relative contribution to GDP. With data on output, capital, and labor available for most countries, the capital deepening component can be estimated with the help of factor prices. The contribution of TFP growth to the overall growth can be calculated as the residual or the difference between the actual overall growth rate and the part of the growth rate accounted for by the growth rate of capital and labor [for a more detailed description, see, e.g., Barro and Sala-i-Martin (2004) or Aghion and Howitt (2009)].

Besides innovation in general, the role of so-called green, environmental, or eco-innovation has received increasing attention. Thus, the essentials of eco-innovations will be described next.

3.1 Eco-innovations

Internationally, the special role played by green, environmental, or eco-innovations for reducing natural resource use has been increasingly recognized, for instance, by the OECD (2008a, 2011c), UNEP (2011a, b), or the European Parliament (2009).

Definitions of this special form of innovations differ slightly depending on the source. Hemmelskamp (1999, p. 16) explains that the definitions revolve around innovations aimed at reducing and avoiding environmental pressures caused by human actions, the remediation of already existing damages, as well as innovations aimed to diagnose and control environmental pressures. The Eco-Innovation Observatory defines eco-innovation as follows:

> "Eco-innovation is the introduction of any new or significantly improved product (good or service), process, organisational change or marketing solution that reduces the use of natural resources (including materials, energy, water and land) and decreases the release

> of harmful substances across the whole life-cycle." (Eco-Innovation Observatory 2012, p. 8)

The OECD understands eco-innovations as innovations that result in reduced environmental impacts (OECD 2008a, p. 20).

Distinctions between different types of environmental innovations differ depending on the source. They seem to evolve firstly around whether they are product or process (and sometimes systems) innovations, and secondly, whether they make use of so-called end-of-pipe technologies or integrated technologies (Hemmelskamp 1999; European Parliament 2009). In the context of eco-innovations process, innovations can be defined as "the implementation of a new or significantly improved production or delivery method," whereas product innovations "include any novel and significantly improved product or service, produced in a way that means its overall impact on the environment is minimized" (European Parliament 2009, p. 14). Systems innovations refer to technological systems as well as to "radical and disruptive technologies that alter market conditions (such as hydrogen and fuel cells) as well as all types of system changes such as industrial, societal or behavioral changes" (ibid, p. 15). Besides these innovations, the European Eco-Innovation Observatory also considers material flow eco-innovations. These innovations "capture innovation across the material value chains of products and processes that lowers the material intensity of use while increasing service intensity and well-being" (Eco-Innovation Observatory 2012, p. 9).

The second distinction concerns the question of whether eco-innovations make use of end-of-pipe technologies or integrated technologies. End-of-pipe technologies refer to disposal processes and recycling technologies that are used after the production or consumption process. They transform, remove, or reduce the outputs (OECD 2007). Integrated technologies, in contrast, work at the emissions source and include all measures that reduce the material and energy input as well as emissions (Adler et al. 1994 cited in Hemmelskamp 1999).

Innovations, as well as eco-innovations specifically, are subject to two forms of associated externalities (OECD 2001d, 2008a):

Positive externalities occur due to knowledge spillovers, whilst negative externalities occur in association with environmental impacts. In the case of positive externalities, the innovator has to bear the full cost of the innovation, but the returns on investment in eco-innovation are not exclusive to the innovator. Thus, the OECD (2008a, p. 24) argues that the rate of innovation might be suboptimal and the economy as a consequence may be less competitive and productive than it could be.

Secondly, polluters receive the full benefits of utilizing the environment; however, they do not have to pay the full cost associated with it. The theory of induced innovation implies that in this case, as price signals are distorted, innovation will be more pollution-intensive than would otherwise be the case.

However, the two different, characteristic forms of externalities associated with eco-innovations lead to different policy responses, often drawn up by the different responsible authorities and this can, in some cases, lead to policy incoherence.

For example, environmental policy measures aimed at fostering eco-innovation may be counteracted by measures fostering innovation in general supporting polluting technologies. Increasing efforts have been made in order to consolidate the two policy aims and a majority of OECD countries have embedded environmental concerns in their science and technology strategies (Goel and Hsieh 2006; OECD 2008a).

The OECD (2008a) also discusses the determinants of eco-innovation, claiming that the factors affecting innovation in general are also relevant for eco-innovations. Those include market firm-level factors such as the degree of market competition, the degree of economic "openness," financing possibilities, and firm size. In addition policy factors such as stable macroeconomic conditions, low and stable interest rates, open international trade, foreign investment policies, and regulation intensity are relevant in the context of eco-innovation. Moreover, the environmental policy framework plays an important role (OECD 2011c).

The measuring of eco-innovation proves to be even more difficult than measuring innovation in general. A list of different input and output measures as well as their limitations can be found for example in OECD (2008a). The three major approaches to support green innovations are the funding of relevant research, the targeting of barriers to early-stage commercial development, as well as demand-side innovation policies (OECD 2011c). An overview of specific tools can be found in OECD (2011c), and a detailed overview on the European approaches can be found in European Parliament (2009). Moreover, in 2009 the European Union pushed the topic of eco-innovation up on its agenda, and studies on eco-innovations within the European Union are conducted by the Eco-Innovation Observatory at regular intervals.

In general, the result of environmental policies is either a change in the costs of factor inputs, for instance, in the case of CO_2 emission certificates, or a change in the relative price of goods and services produced, such as in the case of a tax on fuel. Thus, it is likely that there are increased returns to environment-saving production processes and products, and thus, eco-innovations are induced via environmental policy (OECD 2008a).

3.2 Induced Innovation and the Direction of Technological Change

The basic idea of induced innovation is, in short, that a change in the relative price of a good will lead not only to a change in consumption patterns but also to a change in the direction of technological progress. This can for instance be applied to environmental problems. Newell et al. (1999) argue that if energy prices rise relative to the prices of other goods, the energy intensity of an economy will fall because people change their behavior. Thermostats will be turned down and people will drive slower in order to save energy, furnaces will be replaced with more efficient models available on the market, and over the long run “the pace and direction of technological change would be affected, so that the menu of capital goods available for purchase would contain more energy-efficient choices” (ibid, p. 941).[2]

This idea of economizing the relatively more expensive factor goes back to J.R. Hicks (1932), who argues that “a change in the relative prices of the factors of production is itself a spur to invention and to inventions of a particular kind—directed at economising the use of a factor which has become relatively expensive” (Hicks 1932, p. 124). This is the basic idea of the “induced innovation” hypothesis. In consequence, induced innovations might also influence the direction of technological progress. It took until the 1960s and 1970s until the hypothesis was more prominently discussed.

The role played by factor endowments in determining the direction of technical change appeared on the agenda in the early 1960s (Ruttan 2001). There are two different primary forms of induced innovation, namely, innovation induced by factor prices and innovation induced by factor incomes.[3] The next paragraph outlines the main idea and issues arising with the theory of induced innovation. The following paragraphs briefly present the two major approaches to model induced innovation: the macroeconomic and the microeconomic approach.

Factor price-induced innovation is the original form that Hicks had in mind when he coined the term. This type of innovation can be the result of increased labor costs or increased capital costs. The basic idea is that changes in the relation of the different costs induce substitution processes which then enable and induce the application of technically and economically superior production methods. There are, however, a few conceptual problems. In neoclassical theory, entrepreneurs use the factors of production in such a way that all uses exhibit the same productivity effect and all factors are paid their marginal product. Therefore, if the minimal cost combination is realized, the marginal amounts of the factors are all equally expensive. One factor becoming more expensive can only mean that the entrepreneur sticks to a combination that is no longer (or not yet) optimal given the factor prices. In this case, a simple factor substitution, i.e., a movement along the production function, could solve the problem. Viewed from this angle, the concept only makes sense if one assumes that capital intensification goes hand in hand with the introduction of new, improved production methods. Then, an increase in the wage rate leads to substitution, which is in turn connected to technological progress. Problems with this view include the fact that technological progress and substitution now occur simultaneously and thus cannot be separated. This also means that no clear-cut statement about the nature of technological progress can be made, i.e., how much labor saving originates from capital intensification and substitution and how much from technological progress itself. Additionally, it is not clear that only

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[2] Further analyses of induced innovation and energy prices or energy policy can be found, for example, in Popp (2002), Smulders and de Nooij (2003), and Johnstone et al. (2010).

[3] For the following, see Walter (1969).

because technological progress saves labor it saves more labor than it saves other factors. These problems can be overcome by examining the argument by Fellner (1961), who argues that an entrepreneur acts rationally if he chooses the production process that requires the least labor input, given the rising trend of capital intensity and the wage/interest rate ratio.[4]

Moreover, a conceptual issue concerning factor price-induced technological progress boils down to the question of whether one can distinguish between factor price-induced technological progress and technological progress induced factor prices.

The difficulty of speaking of "expensive" or "cheap" input factors in the context of a minimal cost solution and thus explaining factor price-induced technological progress does not arise when the factor price relations and their expected trends are considered. This is the macroeconomic approach to induced innovation (Walter 1969).

The following theory has its origins in trying to explain why in the USA, factor shares to labor and capital had remained relatively stable despite substantial capital deepening (Ruttan 2001). Kennedy (1964) formulated a growth theoretic approach to induced technical change. The basic idea of the model is as follows[5]: a given trend exists in the factor price relation and entrepreneurs predict that this trend will continue in the future. Moreover, there exist technical alternatives that allow an economic choice, i.e., a given production and a production process that ensures a relative saving of the more expensive factor as well as a new equilibrium given the expected future factor price relation. This argument is not restricted to the size or the development of the wage rate relative to the interest rate. Rather it is also plausible when one considers the share that both cost blocks have on the total costs. For example, if the share of labor costs is higher than that of capital costs, it is worthwhile searching for labor-saving innovations because a 10 % cost reduction has a greater impact if it applies to the factor accounting for say 70 % of total cost than it has for the remaining 30 %. The theory received severe criticism among others for not allocating resource to inventive activity. As Ruttan (2001, p. 102) argues, the theory "has never recovered from the criticism of its inadequate microeconomic foundation."

The microeconomic approach developed by Ahmad (1966) builds directly on the ideas of Hicks. He developed a model which prominently features a so-called innovation possibility curve (IPC). He describes it as an "envelope of all the alternative isoquants (representing a given output on various production functions)

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[4] Capital cost-induced technological progress does not seem to play a major role in the academic debate. The idea is that an increase in the capital cost may induce technological progress aimed at absolutely reducing the more expensive factor. In contrast to labor cost-induced technological progress, the substitution mechanism taking place does not substitute labor for capital but rather substitutes better and more efficient capital for capital. In the course of this process, it is however possible that new, better capital requires less labor to operate it, so that in the end, the net result may be a relatively labor-saving technological progress; see Walter (1969).

[5] See Ruttan (2001) and Walter (1969) for a brief overview.

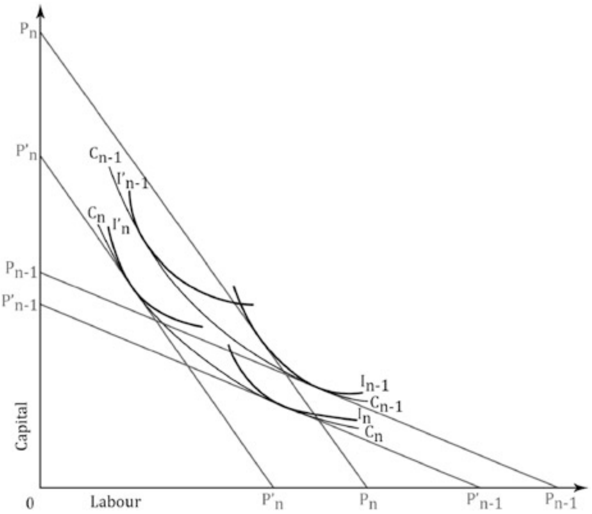

Fig. 3.1 The microeconomic approach to induced innovation. *Source*: Ahmad (1966, p. 349)

which the businessman expects to develop using the available amount of innovating skill and time" (Ahmad 1966, p. 347). This IPC is assumed to be neutral, i.e., there is no technological bias in innovation (Fig. 3.1). I_{n-1} describes the $(n-1)$th invention, i.e., available technological progress at time $n-1$, given the factor price relation $P_{n-1}P_{n-1}$ and cost-minimizing behavior. If the price of labor increases, the new factor price relation now corresponds to P_nP_n. As the IPC determines the isoquant and the production function of the firm until the next innovation occurs, the only thing the firm can do is choose another point on I_{n-1} according to the new factor price relation, and the usual factor substitution takes place. In the next period, however, a new innovation can take place, represented by C_n and the corresponding innovation/technology is chosen according to the price $P'_nP'_n$ $(=P_nP_n)$, represented by I'_n. The effect of a change from I_{n-1} to I_n can be clearly seen in the figure; I_n is more labor saving than I_{n-1}. "Hence a rise in the price of labour would lead to an innovation which is necessarily labour-saving, if the innovation possibility is technologically unbiased" (Ahmad 1966, p. 349). Ruttan (2001, p. 105) adds that if considering a multi-period model, the shift from I_{n-1} to I'_n would "occur in a series of steps in response to incremental shifts" from the old to the new factor price relation.

Based on the approach by Ahmad [further developed by Hayami and Ruttan (1970)], a whole range of empirical tests of the hypothesis were conducted. First, the focus lay on the examination of induced innovation in agriculture, but the examinations were soon expanded to industrial sectors. Yet, the results of the different studies are inconclusive. While Ruttan (2001, p. 108) argues that there is "sufficient support to the view that changes [..] in relative factor endowments and prices exert a substantial impact on the direction of technical change," others such as Liu and Shumway (2009) found little evidence for the hypothesis using three different econometric methods and argue that their findings "caution[s] against the efficacy of policies based on the premise that price signals alone induce efficient technical change" (ibid, p. 235).

The type of technical progress is closely related to induced innovation. Three types of technical progress can be found in the literature, as defined by Hicks, Harrod, and Solow. Hicks-neutral technical progress has a symmetrical productivity effect, i.e., it augments the productivity of all production factors proportionally and therefore operates as an increase in the production factors, given constant productivity. Harrod-neutral technical progress displays an asymmetrical productivity effect, improving the productivity of labor. It works like an increase in the amount of labor given constant productivity, and thus expressed in efficiency units, the amount of labor increases; therefore, it is termed "pure labor augmenting." The Solow-neutral type of technical progress is "pure capital augmenting," i.e., it works analogously, increasing the amount of capital in efficiency units (Rose 1995).

In the context of labor-augmenting technical progress, the labor market effects of this type of technological progress have been of interest for economists, especially for classical economists since the eighteenth century (Hagemann and Kalmbach 1983; Mettelsiefen 1981). The central question was whether technological progress in the form of labor-augmenting technical progress leads to an increased labor displacement, and thus so-called "technological unemployment", or whether a compensation mechanism exists that leads to full employment. The two positions in the debate include the argument that technological progress will compensate its efficiency increases with endogenous mechanisms, as well as the argument that if there is no increase in production, then technological unemployment will occur. The endogenous compensation mechanisms include the arguments regarding additive product innovations, purchasing power compensation, machinery production, international competitiveness, and factor substitution (Hagemann 1985).

This idea of technological unemployment is what policy makers have in mind when they advocate the importance of innovations for a reduction of natural resource use (and consequently decoupling of economic growth from resource use and environmental pressures). With policies to reduce externalities by including all relevant information in the prices, they aim at inducing innovation in order to increase resource or material productivity. These innovations steer technological progress as a whole in a direction where it acts as "natural resource augmenting." This can, in parallel to the debate about technological unemployment, be understood as "technological unemployment" of natural resources.

However, it has been argued by Hagemann (1985) for the case of labor that it is very difficult if not impossible to estimate the effects of technological progress on employment. He points out that additional product innovations may be part of a compensation effect of technological unemployment. The actual effect on employment, however, depends strongly on the kind of innovation. For additive innovations, the effect may be positive; in the case of substitutive innovations, the positive effects of demand for new goods have to be compared with the negative effects of the replacement of existing products.

Transferring this insight to the case of dematerialization implies that the secondary effects of new technologies have to be considered carefully as well as the nature of innovations (additive versus substitutive). In addition this underlines the importance of avoiding a rebound effect.

The following two chapters present the methods for a systematic analysis of material productivity development. Firstly, a method for analyzing development patterns and empirical regularities of economic variables—convergence analysis—is presented. This is a framework widely used for analyzing empirical regularities in growth and development contexts. Secondly, a method for measuring material flows is presented as well as a review on productivity indicators, including their benefits and limitations.

Chapter 4
Convergence: Theory, Econometrics, and Empirics

4.1 Models of Economic Growth and Convergence

The examination of convergence is motivated by the fact that small differences in growth rates of economic growth can—over time and due to compounding—lead to large differences in the welfare levels of economies. This idea is the starting point for the empirical analyses of economic growth, focusing on three major questions: How can the enormous global differences in income and growth be explained? How does the international distribution of per capita income develop over time? What are the prospects for income convergence in an international cross section? The second and the third question are dealt with using convergence analysis. Model predictions regarding the presence or absence of convergence depend upon the assumptions of the growth model in terms of the production function. More precisely, it depends on whether decreasing or increasing returns to scale are present and the extent to which technology diffusion takes place (Hemmer and Lorenz 2004, pp. 1, 20). Section 4.1.1 presents the theoretical starting point for an analysis of convergence—the neoclassical Solow–Swan growth model. In Sect. 4.1.2 a proponent of an endogenous growth model in which convergence is possible will be presented.

4.1.1 The Solow–Swan Model of Growth

The works by Solow (1956) and Swan (1956) form the starting point for the so-called neoclassical growth model. The description here of the model and its workings is based on the textbooks of economic growth by Aghion and Howitt (2009), Barro and Sala-i-Martin (1995, 2004), Frenkel and Hemmer (1999), as well as Romer (2005). A simplified version of the Solow–Swan model is described which conveys its basic idea and working mechanism. This allows the transport of content relevant for a convergence analysis, without being overburdened by detail.

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Before the model is described, basic assumptions concerning the structure of the Solow–Swan growth model and the neoclassical production function will be presented.

4.1.1.1 The Basic Assumptions and the Neoclassical Production Function

The basic assumptions of the Solow–Swan model concern the properties of the production function as well as the evolution of the inputs into production. Before these two are presented, a few basics concerning the model structure are mentioned.

It is assumed that households own the production inputs and assets of the economy and choose the fraction of their income that they consume; the remainder is savings. Each representative household decides whether or not they work, and how much, and if and how many children they will have. Firms hire capital and labor as inputs and produce goods, which they then sell to the households. In order to transform inputs to outputs they have access to technology, which may evolve over time. Finally, relative prices of inputs and produced goods are determined by supply and demand in the markets that exist for firms to sell their goods to households and other firms, and vice versa. In the simplified setup presented here, markets and firms are not taken into consideration.

A household is also a producer and at the same time owns its own inputs and uses technology to transform inputs to outputs. Capital K and labor L as well as knowledge or technology A are used to produce the output Y. The production function with respect to time, denoted by t, thus takes the form

$$Y(t) = F[K(t), L(t)A(t)] \tag{4.1}$$

In the neoclassical growth model with exogenous technological change the production function includes a technology term $A(t)$. This technology or technological progress is non-rival and non-excludable, i.e., all economies have access to the same level of technological progress. Thus, it is basically an international public good which grows at a constant rate g. Technological progress enters multiplicatively with labor, and thus it increases the amount of labor and it is therefore called labor-augmenting or Harrod-neutral technological progress. The term $A(t)L(t)$ is also referred to as the "effective" supply of labor or *effective labor*.

Because the properties of the production function significantly affect the behavior of capital and output, some basic properties of the neoclassical production function will be discussed using the example of the above production function.

The Neoclassical Production Function

The neoclassical growth theory uses an aggregate production function. The output Y depends on capital K, on labor L, and on technology A so that

$$Y = F(K, \mathrm{A}L) \tag{4.2}$$

This implies both a given state of technological knowledge and a certain institutional and sociocultural framework. It is assumed that this function is continuously differentiable, which implies that the factors can be substituted for one another so that a given output can be produced with different factor combinations of K and AL.

It is also assumed that the production function possesses linear homogeneity and thus exhibits constant returns to scale. Doubling the amount of K and L while leaving A fixed will double the output produced. Put differently, if both arguments of the production function are multiplied by a nonnegative constant c output will change by the same factor c.

$$F(cK, cAL) = cF(K, AL) \quad \text{for all}\, c \geq 0 \tag{4.3}$$

This assumption allows writing the production function in its intensive form. Setting $c = 1/AL$ in Eq. (4.3) yields

$$F\left[\frac{K}{AL}, 1\right] = \frac{1}{AL}F(K, AL) \tag{4.4}$$

The term K/AL represents the amount of capital per unit of effective labor and the term on the right-hand side $F(K,AL)/AL$ corresponds to Y/AL the output per unit of effective labor. It is defined: $k = K/AL$, $y = Y/AL$, and $f(k) = F(k,1)$. So, Eq. (4.4) can be rewritten as

$$y = f(k) \tag{4.5}$$

Thus, output per unit of effective labor can be written as a function of capital per unit of effective labor. If one unit of effective labor corresponds to one worker, then the labor productivity function corresponds to the production function per capita. The capital per unit of effective labor is also called *capital intensity*. The necessity of the linear homogeneity of the production function now becomes clear: if the assumption of linear homogeneity was violated, then a proportional factor variation (which leaves k unchanged) would result in non-proportional changes in the production and thus labor productivity. The result would be that for a given capital intensity there might exist a whole range of outputs per unit of efficient labor depending on the absolute factor input level. Consequently, the function in Eq. (4.5) would not be uniquely identified.

Another property of the neoclassical production function, which is essential for convergence, is the diminishing returns to capital accumulation. Firstly, a neoclassical production function exhibits positive and diminishing marginal products with respect to each input, for $K > 0$ and $L > 0$:

$$\frac{\partial F}{\partial K} > 0, \quad \frac{\partial^2 F}{\partial K^2} < 0$$
$$\frac{\partial F}{\partial L} > 0, \quad \frac{\partial^2 F}{\partial L^2} < 0 \tag{4.6}$$

Thus, every additional capital good generates a positive marginal product, which however decreases over time. Secondly, the production function meets the so-called *Inada conditions*. These conditions imply that the marginal product of capital (or labor) approaches infinity, as capital (or labor) goes to zero, and vice versa; the marginal product declines as capital (or labor) increases towards infinity.

$$\lim_{K\to 0}(F_K) = \lim_{L\to 0}(F_L) = \infty$$
$$\lim_{K\to\infty}(F_K) = \lim_{L\to\infty}(F_L) = 0 \tag{4.7}$$

The intuition behind this is that if workers are continuously equipped with more of the same capital goods without new uses for the capital, then at some point in time an additional capital good will become redundant and its marginal product will approach zero. If these two properties are fulfilled the production function will be concave.

A production function that is considered a reasonable description of actual economies is the Cobb–Douglas production function:

$$Y = F(K, AL) = K^{\alpha}(AL)^{1-\alpha} \tag{4.8}$$

where $A > 0$ is the level of technology and α is a constant with $0 < \alpha < 1$. In its intensive form, i.e., in per capita terms it can be written as

$$y = f(k) = F\left(\frac{K}{AL}, 1\right) = \left(\frac{K}{AL}\right)^{\alpha} = k^{\alpha} \tag{4.9}$$

Because $f'(k) = \alpha k^{\alpha - 1} > 0$ and $f''(k) = -(1-\alpha)\alpha k^{\alpha - 2} < 0$ one can see that $\lim_{k\to\infty} f'(k) = 0$ and $\lim_{k\to 0} f'(k) = \infty$. So, the Cobb–Douglas production function satisfies the properties of a neoclassical production function.

The Evolution of the Inputs into Production

Before the dynamics of the model are presented, the evolution of the inputs into production will be described. It is assumed that the initial values of the inputs capital, labor, and technology are given.

The labor force L is amongst others determined by population growth, which in turn is influenced by fertility, mortality, and migration. It is assumed that population growth occurs at an exogenous, constant, and positive rate n

$$\dot{L}(t) = nL(t) \tag{4.10}$$

A dot over a variable represents its derivative with respect to time, so $\dot{L}(t) = \mathrm{d}L(t)/\mathrm{d}t$. Population is normalized to 1 at $t = 0$ and every person works at a given intensity which is also set equal to 1, so that population and labor force grow according to

$$L(t) = e^{nt} \tag{4.11}$$

Technology also grows with an exogenous, constant, and positive rate g.

$$\dot{A}(t) = gA(t) \tag{4.12}$$

So, technology at time t is represented by

$$A(t) = A(0)e^{gt} \tag{4.13}$$

The evolution of capital depends on the saving rate and on depreciation. Generally, the output $Y(t)$ can be consumed $C(t)$ or invested $I(t)$ in order to obtain new units of physical capital. Thus $Y(t) = C(t) + I(t)$. As the economy is closed, output equals income. Also, the amount saved corresponds to the amount invested, $S(t) = Y(t) - C(t) = I(t)$. The fraction of output devoted to saving and thus investment, the *saving rate* $s(\bullet)$, can be used to describe the fraction of output that is consumed, namely, $1-s(\bullet)$. A constant, positive saving rate is assumed. The depreciation of existing capital proceeds at a constant rate of $\delta > 0$.

Thus the net increase of the capital stock at a fixed point in time is determined by gross investment minus depreciation, i.e.,

$$\dot{K}(t) = I(t) - \delta K(t) = s \cdot Y(t) - \delta K(t) \tag{4.14}$$

Next, the behavior of the economy will be described. The evolution of the variables labor and knowledge is determined by factors from outside, i.e., exogenous to the model. As a consequence, the behavior of the economy is determined by the behavior of the third input factor, capital.

4.1.1.2 The Dynamics of the Solow–Swan Model with Exogenous Technological Change

For the dynamics of the model, the focus lies on the capital stock per effective unit of labor k. Since $k = K/AL$ the chain rule can be used to obtain

$$\begin{aligned}\dot{k} &= \frac{\dot{K}(t)}{A(t)L(t)} - \frac{K(t)}{[A(t)L(t)]^2}\left[A(t)\dot{L}(t) + L(t)\dot{A}(t)\right] \\ &= \frac{\dot{K}(t)}{A(t)L(t)} - \frac{K(t)}{A(t)L(t)}\frac{\dot{L}(t)}{L(t)} - \frac{K(t)}{A(t)L(t)}\frac{\dot{A}(t)}{A(t)}\end{aligned} \tag{4.15}$$

From Eqs. (4.10) and (4.12) it is given that $\dot{L}(t)/L(t) = n$ and $\dot{A}(t)/A(t) = g$. It is also known that K/AL is k, Eq. (4.5) gives that $f(k) = Y/AL$, and Eq. (4.14) gives $\dot{K}(t)$. Substituting them into Eq. (4.15) yields

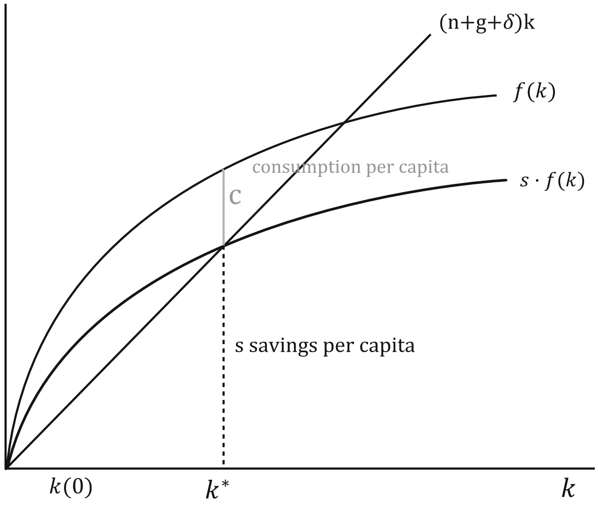
$$\begin{aligned}\dot{k}(t) &= \frac{s \cdot Y(t) - \delta K(t)}{A(t)L(t)} - k(t)n - k(t)g \\ &= s\frac{Y(t)}{A(t)L(t)} - \delta k(t) - nk(t) - gk(t) \\ &= s f(k(t)) - (n + g + \delta)k(t)\end{aligned} \tag{4.16}$$

This equation is the fundamental differential equation, i.e., the law of motion of the Solow–Swan model with technology. It shows that the rate of change in the capital stock per effective worker is determined by two terms. The first term on the right-hand side of the equation $s\,f(k)$ is the investment per unit of effective labor. The second term $(n + g + \delta)k$ is the *break-even investment*, the investment required to keep k at its present level. Investment is needed to maintain k at its present level for two reasons: Firstly, new capital is necessary to replace depreciated capital. Secondly, the growing amount of effective labor needs to be equipped with capital. As the quantity of effective labor grows at the rate $n + g$, the capital stock also needs to grow with $n + g$ to keep the capital intensity k steady. Consequently, when actual investment is larger than break-even investment the capital stock per unit of effective labor will rise. Conversely, if actual investment is lower than break-even investment k will fall. Capital intensity is constant when the two are equal.

Figure 4.1 shows graphically how Eq. (4.16) works. There are three components: the production curve $f(k)$, the savings curve $s{\cdot}f(k)$, and the straight 45° line from the origin with a positive slope $n + g + \delta$, representing the $(n + g + \delta){\cdot}k$ term in Eq. (4.16).

In an economy with $k(0) > 0$ investment per unit of effective labor corresponds to the height of the $s{\cdot}f(k)$ curve at $k(0)$ and consumption corresponds to the vertical difference between $f(k)$ and $s{\cdot}f(k)$. The change of k can be read off the difference between $s{\cdot}f(k)$ and $(n + \delta){\cdot}k$. The $s{\cdot}f(k)$ curve starts from the origin, just as the production function because $f[0] = 0$. It has a positive slope as $f'[k] > 0$; this slope gets flatter as k increases because $f''[k] < 0$. Just as for the production function, the Inada conditions also imply for the savings curve that it is vertical at $k = 0$ and becomes a flat, horizontal line as k approaches infinity. Due to the fact that the slope of the saving curve falls towards zero as k increases, the saving curve will at some point in time cross the break-even investment line and will consequently lie below

Fig. 4.1 The Solow–Swan model. *Source*: Barro and Sala-i-Martin (1995, p. 18)



it. The value of k where actual investment and break-even investment intersect is denoted k^*. The behavior of $\dot{k}$ can be summarized in a phase diagram (see Fig. 4.2).

In this diagram in $\dot{k}$ is shown as a function of k. If, initially the capital intensity per unit of effective labor k is smaller than the so-called steady-state value k^* actual investment is larger than break-even investment, so $\dot{k}$ is positive and consequently k rises. If k exceeds k^*, $\dot{k}$ is negative. When k is equal to k^*, $\dot{k}$ is zero; thus k does not change. Independent of the starting point of k, it moves towards k^*.[1]

Next, the behavior of the variables when k equals k^*, thus when the economy is in the steady state, is described. It is assumed that labor and knowledge or technology grow at constant rates of n and g, respectively. As k is constant at k^* the capital stock K grows with the growth rate of effective labor, $n + g$. Thus, as capital and labor grow with $n + g$, output Y also grows with that rate, because of the assumption of constant returns to scale. Capital per worker, K/L, and output per worker, Y/L, both grow at the rate g. Summing up, the Solow–Swan model with technological progress implies that regardless of the starting point of an economy, it will converge towards a *balanced growth path,* on which each variable of the model grows at a constant rate. The growth of the variables as a constant rate is sometimes also termed *steady state.* In the steady state or on the balanced growth path output per worker solely depends on the (exogenously given) rate of technological progress.

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[1] If initially $k = 0$ it will remain zero. This possibility is ignored here.

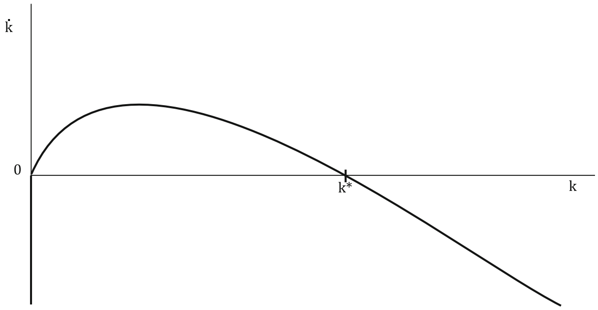


Fig. 4.2 Solow model phase diagram. *Source*: Romer (2005, p. 16)

Convergence in the Solow–Swan Model

One of the essential implications of the Solow–Swan model is the implication that smaller values of k are associated with higher growth rates of k. This implies that economies with lower values of capital per unit of effective labor are able to realize higher growth rates; thus the model implies that *convergence* across economies takes place. To see this the growth rate of capital per unit of effective labor

$$\gamma_k = \dot{k}/k = sf(k)/k - (n + g + \delta) \tag{4.17}$$

is introduced by dividing Eq. (4.16) by k. Deriving γ_k with respect to k yields

$$\frac{\partial \gamma_k}{\partial k} = s \cdot \left[f'(k) - f(k)/k \right] / k \tag{4.18}$$

This derivative is negative because the growth rate of the capital intensity $f'(k)$ is positive but decreases over time, the average product of capital $[f(k)/k]$ is positive and increases over time, and k is positive. This implies that smaller values of k go hand in hand with higher values of γ_k.

To illustrate this, a group of closed economies is considered. They have the same structural parameters (n, s, δ) and the same production function $f(\bullet)$. Consequently, they will also share the same values for k^* and y^*. Due to past disturbances such as wars or transitory shocks to the production function the economies differ, however, in their initial capital intensity $k(0)$. The model implies that the initially poorer country, i.e., lower $k(0)$ and $y(0)$ in the beginning, is able to realize higher growth rates of k. This can be seen in Fig. 4.3.

This figure shows the behavior of the growth rate. From Eq. (4.17) it is known that the growth rate of the capital stock per unit of effective labor depends on two terms: the product of the saving rate and the average product of capital per unit of effective labor as well as the effective depreciation $(n + g + \delta)$. These two are plotted against k in the Fig. 4.3. The $sf(k)/k$ curve is downward sloping and the effective depreciation is represented by a vertical line. At the point where the two intersect the growth rate of k is zero. The growth rate of k corresponds to the vertical distance between the $sf(k)/k$ curve and the depreciation line. The growth rate of k is

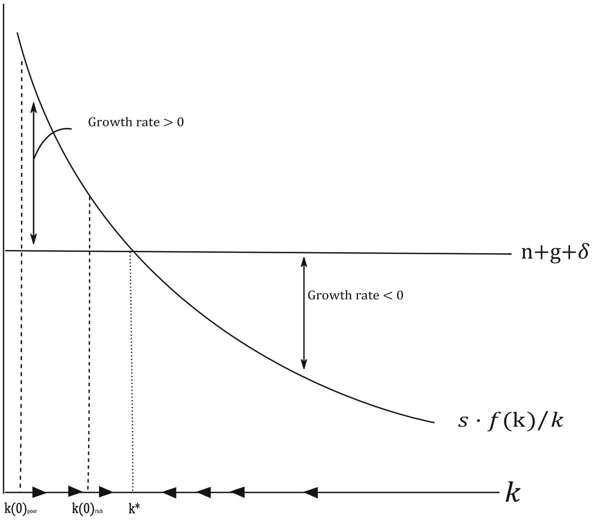


Fig. 4.3 Barro diagram. *Source*: Barro and Sala-i-Martin (2004, p. 38)

positive as $k < k^*$ and it is negative as $k > k^*$. Along the transition from a low level of capital per unit of effective labor the growth rate of k declines monotonically towards zero. Moreover, two economies are distinguished in Fig. 4.3, a rich economy with a higher initial value of k, $k(0)_{\text{rich}}$, and a poorer economy with a lower initial value $k(0)_{\text{poor}}$. As the economies do not differ in their basic parameters, the dynamics of k are for both economies determined by the same curves. Thus, one can see that the growth rate of the initially poorer economy exceeds the growth rate of the initially richer economy. The result of this is a form of convergence, the so-called *absolute convergence*, i.e., less capital intensive economies catching up with economies with higher capital intensity.

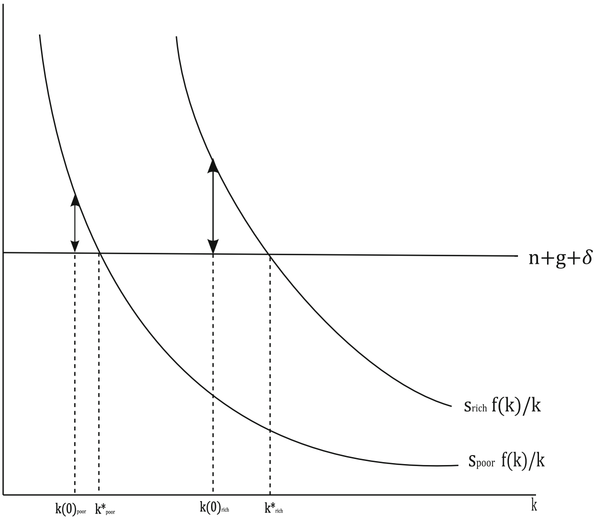
Another form of convergence is the so-called *conditional convergence*. Here, different parameters and thus steady states are assumed (and allowed), and consequently, economies that are further from their own steady state grow faster than economies closer to it. In the context of conditional convergence it is therefore possible that a poorer country grows slower than a richer country if the poorer country is positioned closer to its steady state than the richer country. Consequently, the neoclassical model implies that countries converge towards their own steady state and that the speed of convergence is inversely related to the distance to the steady state. This can be seen in Fig. 4.4.

More formally, the concept of conditional convergence can be described as follows: The growth of per capita capital is determined by the saving rate (amongst others). As the capital intensity does not change in the steady state the condition for the saving rate in the steady state (based on Eq. 4.16) can be expressed as

$$s = (n + g + \delta) \cdot k^* / f(k^*) \tag{4.19}$$

Replacing s in Eq. (4.17) yields

Fig. 4.4 Conditional convergence. *Source*: Barro and Sala-i-Martin (2004, p. 42)



$$\gamma_k = (n + \delta) \cdot \left[\frac{f(k)/k}{f(k^*)/k^*} - 1\right] \tag{4.20}$$

It can be seen that $\gamma_k = 0$ if $k = k^*$. With k^* given, a reduction of k will raise the average product of capital $f(k)/k$ and will thus increase the growth rate of k. But it is only true that a lower k leads to higher growth of capital per unit of effective labor if the reduction is relative to the steady-state value k^*. Thus, the more similar the actual average capital productivity and the steady-state average capital productivity are, the lower the speed of growth will be. In other words, a poorer country will not grow faster if its actual capital intensity is not far from it steady-state capital intensity, i.e., if its capital intensity k is similarly low as its steady-state capital intensity k^*.

This implies that in empirical applications, the variables responsible for differences in the steady-state locations should be held fixed in order to investigate the relationship between γ_k and the starting position $y(0)$. For a homogeneous group of economies, such as the US states, absolute convergence can be expected, as differences between the states can be expected to be minor. In a global context, however, significant differences between the steady states can be expected. Additionally, countries with low levels of $y(0)$ might exhibit those low levels because their steady-state level of income is low, possibly due to low saving rates or bad government policies lowering the level of the production function.

The speed with which countries are able to close the gap to their steady state, or in other words the speed of the transitional dynamics, will be discussed next. The aim is to determine how fast k approaches k^*. To do this mathematical approximations around the long-run equilibrium or steady state can be used. The central equation of the model is the equation for the change of the capital stock (Eq. 4.16): $\dot{k} = sf(k(t)) - (n + g + \delta)k(t)$. The change of k is determined by

k and can therefore also be written as $\dot{k} = \dot{k}(k)$. Also, at $k = k^*$, $\dot{k}$ equals zero. So, a first-order Taylor approximation of $\dot{k}(k)$ around $k = k^*$ yields

$$\dot{k} \simeq \left[\frac{\partial \dot{k}(k)}{\partial k} \bigg|_{k=k^*} \right] \cdot (k - k^*) \tag{4.21}$$

This means that in the vicinity of the steady state, $\dot{k}$ is determined by two terms: the difference between k and k^* as well as the derivative of $\dot{k}$ with respect to k at $k = k^*$. Next, λ is set equal to $-\left[\frac{\partial \dot{k}(k)}{\partial k} \Big|_{k=k^*} \right]$. Thus Eq. (4.21) can be written as

$$\dot{k}(t) \simeq -\lambda[k(t) - k^*] \tag{4.22}$$

Sometimes instead of λ the derivative of the change of capital per unit of effective labor is also denoted by β. As it is known that $\dot{k}$ is positive when slightly above k^* and negative when slightly below k^*, the derivative of $\dot{k}$ with respect to k is negative and consequently, λ is positive. From Eq. (4.22) one can see that around the balanced growth path k moves towards its steady-state value k^* at a speed which is approximately proportional to its distance from k^*. Therefore the capital stock per unit of effective labor moves with

$$k(t) \simeq k^* + \mathrm{e}^{-\lambda t}[k(0) - k^*] \tag{4.23}$$

where $k(0)$ is the initial value of k.

In order to learn about λ Eq. (4.16) is differentiated with respect to k and the result evaluated at $k = k^*$. This procedure yields

$$\begin{aligned} \lambda &\equiv -\left[\frac{\partial \dot{k}(k)}{\partial k} \bigg|_{k=k^*} \right] = -\left[sf'(k^*) - (n+g+\delta) \right] \\ &= (n+g+\delta) - sf'\left(k^*\right) \\ &= (n+g+\delta) - \frac{(n+g+\delta)k^* f'(k^*)}{f(k^*)} \\ &= [1 - \alpha_K(k^*)](n+g+\delta) \end{aligned} \tag{4.24}$$

For these transformations the fact that $sf(k^*) = (n + g + \delta)k^*$ is used to substitute for s. Moreover, α_K is defined as $k^*f'(k^*)/f(k^*)$. So, k converges towards its steady state at a rate of $[1 - \alpha_K(k^*)](n + g + \delta)$. It can be shown that per capita output y approaches its steady-state value y^* at the same rate as k approaches k^*. By calibrating Eq. (4.24) and applying typical values observed in reality the actual speed of convergence or the half-life of convergence, i.e., the time after which half of the initial gap is eliminated can be calculated [see Romer (2005) or Barro and Sala-i-Martin (2004)].

Finally, it will be discussed briefly how the so-called β-convergence from above relates to an alternative meaning of convergence, requiring that the dispersion of per capita income falls over time. This second concept of convergence is called *σ-convergence* and demands that "the dispersion of real per capita income across a group of economies tends to fall over time" (Barro and Sala-i-Martin 1995, p. 31). In this context, β-convergence is a necessary but not sufficient condition for σ-convergence, because as they show that the presence or absence of σ-convergence depends on whether the initial dispersion of per capita incomes starts below or above the steady-state dispersion. They argue that especially a rising dispersion, i.e., σ-divergence, is consistent with absolute β-convergence. As Frenkel and Hemmer (1999) argue, it is possible that in the case of conditional β-convergence a richer country grows faster than a poorer economy; therefore it is also possible that β-convergence occurs without σ-convergence.

Barro and Sala-i-Martin (1995) add that the results for convergence and dispersion can also be viewed in the light of the so-called Galton's fallacy [see also Quah (1993)]. This states that while the heights in a family tend to revert towards the mean over time, this does not imply that the dispersion of heights across the full population will decrease over time. Along this line they argue that β-convergence, i.e., the tendency of poorer countries, is not necessarily reflected in a tendency for the dispersion of per capita incomes to diminish. Thus, β-convergence is a necessary but not sufficient condition for a diminishing dispersion of per capita incomes over time. Hemmer and Lorenz (2004) mention that the dispersion does not diminish if random, exogenous shocks constantly disturb the steady-state levels of per capita income. The assimilation of per capita income levels in terms of absolute convergence then depends on both the speed of convergence to the steady state and the frequency and size of the shocks on the steady state. However, if there are country-specific and country group-specific shocks present, the assumption that the error terms of the regression are independent of each other is violated. Consequently, the estimates for the coefficient β will be biased.

Summing up, the Solow–Swan model implies the following results [see Hemmer and Lorenz (2004)]: Firstly, the actual growth rate of GDP results from the growth rates of labor in efficiency units and capital. Secondly, in order for a growth equilibrium to exist, constant growth rates are mandatory. The steady-state growth rate of the entire system is determined by the exogenous growth rate of labor. Savings and thus investment only determine the level of income and not the long-run growth rate. Thirdly, in the steady state the productivity of labor in efficiency units remains constant, but as each worker becomes more productive due to technological progress (Harrod-neutral), the productivity per worker also increases. Finally, due to the assumptions regarding the production function, convergence occurs. Economies which are situated further from their steady-state growth path grow faster than economies already close to it. In the steady state all countries grow at the same rate, namely, the rate of technological progress. Differences in growth rates can therefore be understood to reflect differences in the distance between the actual position and the level of the steady state for the respective countries.

4.1.2 Convergence in Models of Endogenous Growth

The neoclassical models of growth make optimistic predictions regarding to the long-run development perspectives of less developed economies. The fact that the actual development of per capita incomes cannot easily be reconciled with the predictions of the neoclassical growth theory prompted a search for alternative explanations for the growth process. The results of this search are the models of endogenous growth. The distinguishing features of the neoclassical and endogenous growth models can be explained through the essential features of the neoclassical model. Its predictions are determined by the assumption of decreasing marginal returns, as well as the assumption of an exogenous technological change in the form of an internationally available public good. These two assumptions are the main foundation for the endogenous growth theories. If permanent increases in per capita income are to be explained without resorting to exogenous parameters two avenues can be taken. On the one hand, mechanisms can be identified which prevent a constant decrease of the marginal productivity of capital, as this forms a decisive barrier to a continuous growth process of both labor productivity and per capita income. This is the route taken by the first generation of endogenous growth models, the so-called AK models. On the other hand, technological progress can be explained from within the model (endogenous), based on a technological context, preferences, and market structures. This is the mechanism used by Schumpeterian models focusing on research and development (Hemmer and Lorenz 2004, pp. 57f).

The first generation of endogenous growth models includes constant returns to scale in the production function and were developed initially by Romer (1986). Their implications will be discussed only briefly. In these models knowledge externalities play a major role. The production function of the firm demonstrates constant returns to scale, but due to the externalities of investment, these returns to scale are increasing on an economy-wide level. The so-called AK function is a prominent example of this type of production function. As a consequence, the incentive for households to save and invest does not vanish over time. Additionally, a change in the parameters like savings or the technological level has a permanent effect on the growth rate of the system and does not only lead to a change in the level of income as in the neoclassical model. If two economies have the same parameters for saving, technology, population growth, and depreciation, they will grow at the same rate even if they differ in their capital stock and thus per capita income. Convergence will not occur. In contrast, divergence is possible if two economies have the same per capita income but different technologies. In this case the economy with better technologies (i.e., the higher the technology parameter in the production function) will grow faster while the other will grow more slowly. Overall, this means that investment is still worthwhile for rich economies and that they can maintain their relatively better position. For poor economies, this means that not only do they not grow faster than rich economies, but also that they cannot catch up to them.

The second generation of endogenous growth models comprises two branches: models of product variety and Schumpeterian models. These models focus on determining the consequences of the development of new products for an economy. While the neoclassical growth theory focuses strongly on the efficiency of production methods, i.e., process innovations, endogenous growth theory also takes product innovations into account. The models of product variety focus on the effects of the creation of new products, and the so-called Schumpeterian models of growth focus on quality-improving innovations, rendering old products obsolete. These models are called Schumpeterian because they feature the notion of creative destruction that is central to Joseph Schumpeter's work. Schumpeterian models display particularly interesting features relating to convergence as they can cater for patterns of both convergence and divergence (Aghion and Howitt 2009). The basic idea underlying these models is that improvements in the quality of products lead to additional profits for the innovative entrepreneur and grant him or her at least a temporary monopoly for his or her innovation (Erber et al. 1998). In Schumpeterian growth theory convergence occurs through productivity by means of technology transfer as well as through capital accumulation (Aghion and Howitt 2009). Here, the focus will lie on the productivity effects. Following this, the capital accumulation aspect of convergence will be mentioned briefly.

There are two central aspects in the analysis of convergence in Schumpeterian models: *technology transfer* and the idea of the "*distance to the frontier*." Aghion and Howitt (2009) explain how they model the idea of Gerschenkron (1962) of an "advantage of backwardness"—the notion that a country far from the technology frontier can grow rapidly if they adopt technologies developed in more advanced countries. In their model they assume that technology transfer occurs whenever an innovation takes place, because embodied ideas from around the world are implemented if an innovator is successful. They continue that the technology transfer will stabilize the gap between rich and poor countries. Poor countries are able to grow as rapidly as the rich countries, if these countries devote resources to innovation, because innovation is the process that transfers technology. If a country is not innovating, its position will remain static while countries that do innovate will continue to advance. This is exactly what happens when club convergence occurs; a group of innovative countries advances while another group that does not innovate stagnates. Aghion and Howitt further explain that innovation is necessary in order for technology transfer to take place because technological knowledge is often tacit and circumstantially specific. Therefore it is necessary that the receiving country invests resources in mastering and adapting the technology. This may not look like frontier R&D, but analytically has the same characteristics as R&D being "a costly activity building on the ideas of others to create something new in a particular environment" (Aghion and Howitt 2009, p. 152). Note that this model however does not predict a closing of the gap between poor and rich countries. Convergence of levels occurs only if the countries share the same parameters determining the amount of research conducted in an economy.

The following description of the mechanisms leading to club convergence in Schumpeterian growth models is based on the model of Aghion and Howitt (2009).

The model is quite similar to the standard multisectoral Schumpeterian model also described in Aghion and Howitt (2009). The final good is produced with labor and intermediate products according to the production function

$$Y_{it} = L^{1-\alpha} \int_0^1 A_{it}^{1-\alpha} x_{it}^{\alpha} di, \quad 0 < \alpha < 1 \tag{4.25}$$

The input of the intermediate product i is denoted by x_{it} and A_{it} is the productivity parameter or the quality of the intermediate input. Labor input is normalized to 1, i.e., $L = 1$. In the presence of perfect competition the price of each intermediate good equals its marginal product

$$p_{it} = \alpha A_{it}^{1-\alpha} x_{it}^{\alpha} \tag{4.26}$$

The intermediate product i is produced using the final good as an input, one for one. The monopolist will choose x_{it} to maximize his or her profit

$$\Pi_{it} = p_{it} x_{it} - x_{it} = \alpha A_{it}^{1-\alpha} x_{it}^{\alpha} - x_{it} \tag{4.27}$$

From this the equilibrium quantity

$$x_{it} = \alpha^{\frac{2}{1-\alpha}} A_{it} \tag{4.28}$$

and the equilibrium profit

$$\Pi_{it} = \pi A_{it}^{*} \quad \text{with the constant} \quad \pi = (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} \tag{4.29}$$

can be deduced. The potential innovator's probability of success μ is an increasing function $\varphi(n)$ of his or her productivity-adjusted research expenditure $n = R_{it}/A_{it}^{*}$, where R_{it} is the R&D expenditure and A_{it}^{*} is the target productivity level. The probability μ is chosen to maximize the expected payoff

$$\mu \Pi_{it} - R_{it} = [\mu\pi - \widetilde{n}(\mu)] A_{it} \tag{4.30}$$

where $\tilde{n}(\mu)$ is the productivity-adjusted research cost, i.e., the value of n such that $\varphi(n) = \mu$. In contrast to the basic model the convergence model allows the possibility that some countries might not conduct research; therefore the innovation cost function now becomes

$$\widetilde{n}(\mu) = \eta\mu + \psi\mu^2/2 \tag{4.31}$$

and the parameters η and ψ are positive. The marginal cost of innovation then is

$$\widetilde{n}^{\prime}(\mu) = \eta + \psi\mu \tag{4.32}$$

This is positive, even when $\mu = 0$. It is also assumed that $\eta + \psi < \pi$; this ensures that the innovation probability is less than 1. Here, two cases need to be considered:

If $\eta < \pi$ the reward to innovation is larger than the cost, so producers will innovate. If $\pi \leq \eta$ the producers will not innovate.

A successful innovator will implement a technology with a productivity parameter $\overline{A}_t$ which represents the world technology frontier at time t. This assumption of the model is related to the idea of Gerschenkron; a country that lies far behind the world technology frontier can realize the "advantage of backwardness."

The world technology frontier grows at a rate of g, which is determined outside the country. So the sector-specific productivity parameters A_{it} will evolve according to

$$A_{it} = \begin{Bmatrix} \overline{A}_t & \text{with probability } \mu \\ A_{i,t-1} & \text{with probability } 1-\mu \end{Bmatrix}$$

The fact that a successful innovator is able to implement $\overline{A}_t$ is a sign of the presence of technology transfers in the sense that the domestic innovator can use ideas developed elsewhere in the world. The country's average productivity parameter $A_t = \int {}_0^1 A_{it} \mathrm{d}i$ will evolve according to

$$A_t = \mu\overline{A}_t + (1-\mu)A_{t-1} \tag{4.33}$$

Thus, in the fraction μ of sectors where innovation takes place productivity is $\overline{A}_t$ and in the remaining fraction productivity stays the same as in the previous period $t - 1$. The distance between the country's productivity and the world technology frontier is also called the country's "proximity" to the frontier and is measured by

$$a_t = \frac{A_t}{\overline{A}_t} \tag{4.34}$$

i.e., the ratio of the country's average productivity parameter to the parameter of the world technology frontier. Consequently, a higher value indicates a greater proximity to the global frontier. The division of the country's average productivity parameter (Eq. 4.33) by the parameter for the world frontier, $\overline{A}_t$, yields

$$a_t = \mu + \frac{1-\mu}{1+g} a_{t-1} \tag{4.35}$$

If $a_t = a_{t-1}$ one obtains the unique and stable steady-state proximity a^* which is the long-run proximity to the frontier

$$a^* = \frac{(1+g)\mu}{g+\mu} \tag{4.36}$$

The model implies three different results with regard to convergence:

First of all, countries in which the productivity-adjusted profit π is larger than the cost of innovation η, thus $\pi > \eta$, will realize the same growth rates in the long run. This means that all countries that do innovate will ultimately converge to the same growth rate. This is possible because a country further behind the frontier can realize the "advantage of backwardness," thus taking advantage of technology transfer and making bigger technological leaps. Aghion and Howitt demonstrate this effect in their model, because the further behind the frontier a country is situated, the larger is the average size of its innovations:

$$\overline{\gamma} - 1 = \overline{A}_t / A_{t-1} - 1 = (1+g)/a_{t-1} - 1 \tag{4.37}$$

As the growth rate is related to the size of innovations

$$g_{it} = \mu(\overline{\gamma} - 1) \tag{4.38}$$

it becomes clear that the further behind the frontier a country is initially, the higher its growth rate will be. Note that this is only true if $\mu > 0$, meaning that the country is innovating at a positive rate. Then, the steady-state proximity to the frontier will be strictly positive.

In the long run the average productivity of the country A_t will be proportional to the productivity parameter of the technology frontier $\overline{A}_t$:

$$A_t = a^* \overline{A}_t > 0 \tag{4.39}$$

The long-run growth rate of the country will therefore be the growth rate g of the world productivity frontier

$$\frac{A_{t+1}}{A_t} = \frac{a^* \overline{A}_{t+1}}{a^* \overline{A}_t} = \frac{\overline{A}_{t+1}}{\overline{A}_t} = 1 + g \tag{4.40}$$

The model also makes predictions as to how far behind the frontier a country can fall. Once a country has fallen far enough behind the frontier its growth rate and the growth rate of the frontier will be equal and thus the gap between them will no longer increase.

The second result refers to the case of $\mu = 0$, i.e., if the country does not innovate. This implies that all countries with $\pi \leq \eta$ will stagnate in the long run. Because η is an innovation cost parameter it can be influenced for example by macroeconomic conditions, the legal environment, credit markets, or the education system. If these factors influence the parameter negatively, i.e., raise the value of η, the country will stagnate as it is not able to benefit from technology transfer. Its equilibrium proximity a^* to the world productivity frontier is zero.

This theory then implies that there exist one group of countries that grow continuously and are converging towards parallel growth paths with identical long-run growth rates and another group of countries that will increasingly fall behind. It must be noted however that this does not imply that they will converge towards the same income level, because the steady-state proximities of different countries may differ depending on the values of the critical parameters influencing the level of research conducted, such as π, η, and ψ.

Finally, the model by Aghion and Howitt (2009) shows that for countries that do innovate the distance to the frontier is increasing in π (i.e., getting smaller) and decreasing in η and ψ. This result is quite intuitive, for example, as the improvements to the education system reduce the cost parameters η and ψ, and therefore the country will grow faster for a while. As it approaches the frontier, the size of the innovations will decrease and its growth rate will approach the growth rate of the technology frontier g. Its steady-state proximity a^*, however, will be larger now, i.e., the country will be permanently situated more closely to the frontier. This fact allows for the reality of different productivity levels across countries and shows that convergence in productivity levels is conditional on the parameter values. Also, the model shows that the steady-state proximity to the technology frontier is decreasing if the growth rate of the frontier g is increasing. This means that if the global frontier speeds up, i.e., exhibits a stronger growth, the steady-state distance of the countries which innovate but only via technology transfer will decrease. In other words, they will be situated further from the frontier—the cross-country productivity distribution will become wider. One example for this can be found in Aghion and Howitt (2006) where they explain why the productivity gap between the USA and Europe stopped closing in the 1970s or 1980s and instead started to rise again. They argue that from World War II until the 1970s or 1980s Europe was catching up to the frontier. However, because its institutions and policies were not optimal for growth close to the frontier, its growth slowed before the gap to the USA had been closed. Additionally, the productivity growth accelerated in the USA in the 1990s as a result of the information technology revolution; thus the frontier growth rate increased. As the major IT innovations did not originate in Europe, the European growth rate could not keep pace. Europe had to wait until it had fallen sufficiently far behind the frontier, i.e., the distance to the frontier was greater, in order to be able to realize a higher productivity growth.

To conclude, Aghion and Howitt argue that in the light of technology transfer, a country's long-run growth rate does not depend on the parameters of the country. For club members growth depends on the global rate of technological progress which is unaffected by local conditions. Domestic parameter changes that alter the country's growth rate in the basic Schumpeterian model result in a change of the relative productivity level in the club-convergence model. They add that for club members the Schumpeterian model is not very different from a neoclassical model with an exogenous growth rate, where policy changes only have level effects. The

Schumpeterian model differs only in that policy affects the level of productivity, not only physical and human capital per person.

In Schumpeterian growth models capital accumulation process can also take place, which can also explain convergence in growth rates [see Aghion and Howitt (2009, pp. 105–112)]. It will however be discussed only briefly, as the focus of the Aghion–Howitt model is the productivity effect. Capital accumulation can be included in the model via π, because it is partly dependent on κ with $\kappa = (K_t/A_t)$, which is aggregate capital stock per worker. It can be seen that the productivity-adjusted profit function

$$\tilde{\pi}(\kappa_t) = \alpha(1-\alpha)\kappa_t^{\alpha} \tag{4.41}$$

is an increasing function of capital stock per effective worker κ_t. The unit cost of production is also the rental rate of capital $R_{kt} = \alpha^2\kappa_t^{\alpha-1}$. The productivity-adjusted profit function (4.41) is increasing in capital stock per worker κ_t, because the unit cost of production decreases with κ_t. Also the productivity-adjusted level of research n_t is affected by κ_t as an increase of κ_t will increase the monopoly profits, i.e., the rewards for innovation. Additionally, the productivity growth rate g_t will also be an increasing function of κ_t. Specifically,

$$g_t = \mu(\overline{\gamma} - 1) \tag{4.42}$$

Thus the growth rate is determined by the frequency of innovations μ times the size of the innovations $(\gamma - 1)$ as $\mu = \varphi(n)$ with $n = R_{it}/A_{it}^*$ and R_{it} is also dependent on κ_t. Consequently, changes in parameters that alter κ_t, for instance, the saving rate or the depreciation rate, also change the growth rate. Thus, the long-run growth is influenced by conditions underlying the equation determining the level of research as well as by conditions underlying the steady-state capital accumulation. Therefore, as capital accumulation increases the level of research conducted and thus the growth rate, capital accumulation can in this context also contribute to convergence.

The question whether and to what extent cross-country income and/or growth rates convergence can be found in reality has formed the subject of a large number of empirical analyses. Before a collection of the studies that were influential in the analysis of material productivity convergence in this dissertation are presented, the different approaches to examine convergence are discussed.

4.2 The Econometrics of Convergence

The workings of Abramovitz (1986) and Baumol (1986) brought the issue of convergence to the attention of a broad audience. In combination with the availability of new datasets for a large cross section of countries, this led to an "enormous literature testing the convergence hypothesis in one or more of its

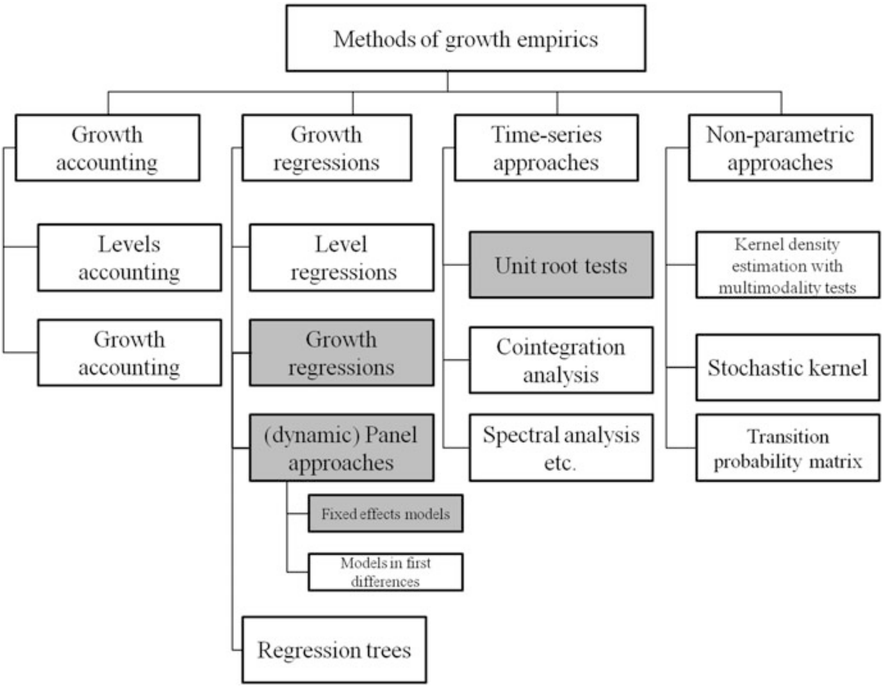


Fig. 4.5 Methods of growth empirics. *Source*: Hemmer and Lorenz (2004, p. 3)

various guises" (Durlauf et al. 2005, p. 582). In general, empirical analysis of economic growth is characterized by the heterogeneity of the different econometric approaches to it. Figure 4.5 provides an overview of the methods of growth empirics.

Growth accounting approaches in the broader sense focus on the question which part of the empirically observed growth can be attributed to advances in technological progress and which part to factor accumulation. Growth regressions in their various guises have proven useful for analyzing the effect of different variables on the per capita income or growth. Time series have been developed as an answer to the shortcomings of cross-sectional convergence analyses and focus stronger on the longitudinal characteristics of the data. Finally, nonparametric distribution approaches focus, as their name implies, on the international distribution of the variable of interest (mostly per capita income) by using descriptive methods. In this dissertation, only a few selected methods from the overall pool of methods are applied for the analysis of material productivity convergence. More specifically, growth regressions, fixed effects models, as well as unit-root tests are conducted in order to examine convergence of material productivity.

This chapter is to a great extent based on the excellent surveys of Durlauf et al. (2005) and Islam (2003b) as well as the book by Hemmer and Lorenz (2004) and presents the econometric methods to examine convergence used in this dissertation. Section 4.2.1 explains the basic ideas behind the notion of convergence and Sect. 4.2.2 describes cross-section and panel methods for examining β-convergence; in Sect. 4.2.3 time-series approaches to convergence are examined and concluding Sect. 4.2.4 explores σ-convergence.

4.2.1 The Basics of Convergence Econometrics

The analysis of convergence developed chronologically: examining absolute β-convergence and then conditional β-convergence. Later the concept of σ-convergence came up. In parallel the concepts of club convergence, TFP convergence, and the time-series approaches to convergence emerged (Islam 2003b).

The starting point for the examination of convergence is the claim, derived from the neoclassical growth model, that in a cross section of countries a negative relationship between average growth rates and initial levels of output is present. This implies that countries which initially are below their balanced growth path have to realize higher growth rates in order to catch up with countries that are characterized by the same levels of steady-state output per effective worker and initial efficiency (Durlauf et al. 2005). Durlauf et al. (2005, p. 582) argue that the question of whether the effects of initial conditions eventually disappear is the heuristic basis for the convergence hypothesis and that it "represents the primary empirical question that has been explored by growth economists." They also argue that it boils down to two questions for researchers in this area, both revolving around permanence: Firstly, are cross-country differences permanent or temporary? And secondly, if they are permanent, is this the result of structural heterogeneity of the countries, or do initial conditions determine the long-run outcomes? Temporary differences in income per capita imply unconditional convergence towards a common long-run level of income per capita. Permanent differences due to structural differences between the countries imply conditional convergence. Convergence clubs can be identified if initial conditions determine at least in some part long-run outcomes, i.e., countries with similar initial conditions will display similar long-run outcomes [see also Galor (1996)]. Following Durlauf et al., the idea that initial conditions are of importance can be formalized into a definition of convergence as follows:

Per capita income ($\log y_{i,t}$) is associated with the initial conditions $\eta_{i,0}$. These $\eta_{i,0}$ do not matter in the long run if

$$\lim_{t\to\infty} \mu\left(\log y_{i,t} \middle| \eta_{i,0}\right) \quad \text{does not depend on} \quad \eta_{i,0} \tag{4.43}$$

where $\mu(\cdot)$ is a probability measure. Convergence between two economies i and j can then be defined as

$$\lim_{t\to\infty} E\left[\log y_{i,t} - \log y_{j,t}\middle|\eta_{i,o}, \eta_{j,t}\right] = 0 \tag{4.44}$$

The main focus of convergence analyses of this type has been on the log level of per capita income (and to a lesser extent total factor productivity). However, they argue, it can be applied to other variables such as real wages or life expectancy, too. Drawing on this idea, this dissertation examines convergence in terms of material productivity. Next, β-convergence, the main technique used to examine long-run dependence, will be presented in more detail.

4.2.2 *β-convergence*

The concept of β-convergence was examined both in the early informal analyses of convergence, which were not formally derived from theoretical growth models, and in the later formal approaches (Islam 2003b). Durlauf et al. argue that β-convergence, defined as $\beta < 0$, can be evaluated easily as it displays the properties of a linear regression coefficient. In a Solow growth model context its interpretation is also easy, as the presence of β-convergence is consistent with the dynamics of the model. Moreover, it allows the speed of convergence to be calculated (Islam 2003b). In brief, in a situation where two countries with common steady-state determinants are moving towards a common balanced growth path, the country with the lower level of initial income exhibits a lower capital–labor ratio and therefore a higher marginal product of capital. With a given rate of investment, this leads to a higher growth rate for the poorer country. More formally, one can see that the parameter β is assigned a crucial role in the dynamics of growth in the Solow model. γ_i stands for the growth rate of output per worker between 0 and t and is described by the following equation:

$$\gamma_i = g_i + \beta_i\left(\log y_{i,0} - \log y_{i,\infty}^{E} - \log A_{i,0}\right) \tag{4.45}$$

with

$$\beta_i = -t^{-1}\left(1 - \mathrm{e}^{-\lambda_i t}\right) \tag{4.46}$$

Here, g_i is the constant rate of labor-augmenting technological progress, log $y_{i,t}^{E}$ is the output per efficiency unit of labor input per capita with log $y_{i,\infty}^{E}$ the steady-state value of log $y_{i,t}^{E}$, log $A_{i,0}$ is the efficiency level of each worker, and log $y_{i,0}$ is the observable initial per capita output. The parameter λ_i depends on the other parameters of the model, for example, steady-state share of capital in income (α), population growth (n), technological progress (g), and depreciation (δ). It measures the rate of convergence of $y_{i,t}^{E}$ to its steady-state value. This equation shows that the growth rate of output per worker consists of two parts: growth due to technological progress which is mirrored in g_i and the second term $\beta_i(\log y_{i,0} - \log y_{i,\infty}^E - \log A_{i,o})$ which measures growth due to the gap between initial output per worker and the steady-state value. Both are displayed in efficiency units as $\log y_{i,0} - \log A_{i,0}$ corresponds to $Y_{i,0}/(A_{i,0}L_{i,0}) = y_{i,0}^E$ in the model setup. As the time horizon increases the importance of the second term diminishes to zero, as do the initial conditions that are reflected in it. In the literature, this second term corresponding to the second source of growth is called "catching up." Therefore the β-term is of crucial importance for the analysis of convergence. Assuming that the rates of technological progress and the λ_i parameters are constant across countries one can conclude from Eq. (4.45) that "in a cross-section of countries, we should observe a negative relationship between average rates of growth and initial levels of output over any time period—countries that start below their balanced growth path must grow relatively quickly if they are to catch up with other countries that have the same levels of steady-state output per effective worker and initial efficiency" (Durlauf et al. 2005, p. 578).

Equation (4.45) has been the starting point for many standard cross-country growth regressions. Usually, an error term ε_i is added so that the equation becomes

$$\gamma_i = g - \beta \log y_{i,\infty}^E - \beta \log A_{i,0} + \beta \log y_{i,0} + \varepsilon_i \tag{4.47}$$

From this equation the so-called *canonical cross-country growth regression* (Eq. 4.48) can be derived, which allows the inclusion of explanatory variables other than those included in the Solow model. A general representation of this regression is the following:

$$\gamma_i = \beta_i \log y_{i,0} - \psi X_i - \xi Z_i + \varepsilon_i \tag{4.48}$$

with X_i containing a constant, $\log(n + g + \delta)$, and $\ln(s)$ and other control variables being represented by Z_i. This equation has been used extensively to study alternative growth determinants, following the analysis of Barro (1991).

Additionally, β-convergence appears in two forms: conditional and unconditional β-convergence. Econometrically, this distinction is implemented by including control variables or by not including them. If β-convergence is identified and no control variables are used, one speaks of unconditional β-convergence. Unconditional β-convergence tries to answer the question of whether all countries are converging to the same growth path—which is closely related to the question of how long current inequalities will persist in the long run. If controls are used, and β-convergence is identified, it is conditional on control factors; thus conditional β-convergence takes place. In this case, countries only converge to a common growth path, if they share common characteristics of the economy.

Durlauf et al. (2005, p. 586) conclude from existing studies that homogeneous economic units like the states of the USA, the OECD, or the regions of Europe typically support the unconditional β-convergence hypothesis [see also Barro and Sala-i-Martin (2004)]. As DeLong (1988) pointed out, this homogeneity can reflect self-selection. He claims that Baumol's (1986) conclusion of unconditional convergence between 1870 and 1979 is spurious, as his dataset only included 16 economically successful countries. Countries which were successful in 1870 and not in 1979 were excluded. A more heterogeneous group such as a sample of countries worldwide generally does not display a correlation between initial income and average growth.

Regarding the rate of convergence, which can be deduced from λ_i, many cross-section studies find evidence for a rate of 2 % per year with comparably little variation. Barro and Sala-i-Martin (1992) argue that estimates generally range between 1 % and 3 %. In contrast, Quah (1996a) argues that this finding of 2 % might be a statistical artifact unrelated to convergence dynamics. He claims that the samples usually estimated are diverse in terms of geography and time and suggests that the underlying economic structure across countries and regions might not be invariant. This invariance is however a necessary assumption for the validity of the method. Similarly, as argued by Durlauf et al. (2005) and as stated before, the rate of convergence is determined depending on model parameters like preferences, technology, and endowments. A common convergence rate of 2 % across different economic units suggests "remarkable uniformity of preferences, technologies, and endowments" and may therefore be viewed critically (Durlauf et al. 2005, p. 587).

According to Islam (2003b) another issue arises with the parameter λ_i and the growth Eq. (4.45) in a cross-section context: They are both derived from the basis of a growth process *within* an economy. However, researchers estimated the model using cross-section data, as they were interested in the question of whether poor countries are catching up to richer ones, which is an *across* concept. This leads to a problem of interpretation of the convergence parameter λ_i. Technically, λ_i describes the speed at which a country closes the gap towards its own steady state. In cross-sectional convergence analysis it is however often interpreted as the speed with which poorer countries are catching up with richer countries. This does not pose a problem in the case of unconditional convergence, as the poor and the rich countries display the same steady-state level of income. Yet, in the case of conditional convergence the steady states of rich and poor countries differ. Therefore λ_i cannot be interpreted as measuring the speed of convergence, but rather has to be interpreted as the speed of closing the gap towards the country's own steady state. This *within-across* tension arose as the cross-country regression specifications became formally linked to a growth model. Earlier, informal approaches to estimate β did not suffer from this problem as they were limited to the reduced form, cross-sectional interpretation of β, mainly trying to establish whether initial GDP and growth of GDP or labor productivity are correlated inversely [see Abramovitz (1986) or Baumol (1986)].

In addition to the above, the cross-section approach to convergence analysis is subject to a number of limitations, the main one being that there is only one data point per country and this constitutes a poor basis for the estimation of the convergence parameter λ. Islam (2003b, p. 324) argues that "there is too much heterogeneity across countries to validate the assumption that cross-country data can be treated as multiple data of the same country." Additionally, the assumption of identical technologies across countries in the cross-sectional framework hinders the correct estimation of the second term in the growth Eq. (4.45), because if technological differences are present they act as a confounding factor in the data. However, the necessity to econometrically identify the model forces one to subsume the technology term A_0 under the error term in a cross-section framework (see, e.g., Mankiw et al. 1992). Even if proxy variables are included for A_0, which is hard to measure, there will probably still be at least some part of it that remains unobservable or immeasurable and still correlated with the included variables. It is not probable that the technology term (or at least parts of it) is uncorrelated, for instance, with investment or population growth. If the technology term A_0 is included in the error term, however, the omitted variable bias problem occurs. In order to overcome these basic limitations of the cross-sectional approach researchers turned to panel approaches in convergence analysis.

4.2.2.1 Panel Methods of β-convergence Analysis

The panel approach of convergence analysis allows researchers to estimate unobserved effects in panel data models, thus correcting for the omitted variables problem [for the following see Hsiao (2003), Wooldridge (2002a, pp. 247–298), Wooldridge (2002b, pp. 408–460)].

Wooldridge (2002a) argues that panel data can be used, under certain assumptions, to obtain consistent estimators in the presence of omitted variables.

Assuming a linear model with an unobservable random variable c that enters additively with the observable explanatory variables x_j yields the following regression function:

$$E\left(q\middle|\boldsymbol{x},u\right)=\beta_0+\boldsymbol{x\beta}+u \tag{4.49}$$

If u is uncorrelated with the x_j, i.e., it is not related to the observable explanatory variables, it is simply an unobserved factor affecting q. If u is somehow correlated with the x_j for some j, including u in the error term can cause severe problems (omitted variable problem) and β cannot be consistently estimated. When several observations of the same cross-section units at different points in time are available this problem can be solved by random and fixed effects estimation. Fixed effects estimation, commonly used in convergence analysis, will now be presented in more detail.

Suppose y and $\boldsymbol{x}$ can be observed at two different time periods $t = 1, 2$ and that the omitted variable c is time constant of the population regression function then becomes:

$$E\left(q_t\middle|\boldsymbol{x_t},u\right)=\beta_0+\boldsymbol{x_t\beta}+u \tag{4.50}$$

where $x_t\beta = \beta_1 x_{t1} + \cdots + \beta_K x_{tK}$ and x_{tj} indicates variable j at time t. It is assumed that u has the same effect of the mean response in each time period. This type of variable, namely, one which is constant over time and has a constant partial effect over time, is called an unobserved effect. This unobserved effect, also called an individual effect, or individual heterogeneity, can be interpreted as capturing the features of an individual or in this case country that can be assumed to (roughly) remain constant over time (for instance, geography or climate). In an error form the model becomes:

$$q_t = \beta_0 + \boldsymbol{x_t \beta} + u + \varepsilon_t \tag{4.51}$$

for which it is assumed that ε_t is not correlated with x_t or u. Also, variables that are constant across time cannot be included in x_t. For a cross-section observation i the basic unobserved effects model can be written:

$$q_{it} = \boldsymbol{x_{it} \beta} + u_i + \varepsilon_{it} \tag{4.52}$$

Under certain assumptions the pooled OLS estimator can be used to estimate $\boldsymbol{\beta}$ consistently. Writing the model with composite error yields:

$$q_{it} = \boldsymbol{x_{it} \beta} + o_{it} \tag{4.53}$$

with $o_{it} = c_i + \varepsilon_{it}, t = 1,2,\ldots,T$ as composite errors. So that for each t o_{it} is the sum of the unobserved effect and an idiosyncratic error. Fixed effects analysis allows c_i to be arbitrarily correlated with the x_{it}. In order to estimate $\boldsymbol{\beta}$ the equations are transformed so that the unobserved effect u_i is eliminated. The *fixed effects transformation*, also called the *within transformation*, is obtained by averaging Eq. (4.52) over $t = 1,2,\ldots,T$ which yields:

$$\overline{q}_i = \overline{x}_i \beta + u_i + \overline{\varepsilon}_i \tag{4.54}$$

where $\overline{q}_i = T^{-1} \sum_{t=1}^{T} q_{it}$, $\overline{x}_i = T^{-1} \sum_{t=1}^{T} x_{it}$, and $\overline{\varepsilon}_i = T^{-1} \sum_{t=1}^{T} \varepsilon_{it}$. Then subtracting Eq. (4.54) from Eq. (4.52) for each t gives the fixed effects (FE) transformed equation

$$q_{it} - \overline{q}_{it} = (x_{it} - \overline{x}_i)\boldsymbol{\beta} + \varepsilon_{it} - \overline{\varepsilon}_i \tag{4.55}$$

or

$$\ddot{q}_{it} = \ddot{x}_{it} \beta + \ddot{\varepsilon}_{it}, \quad t = 1, 2, \ldots, T \tag{4.56}$$

where $\ddot{q}_{it} = q_{it} - \overline{q}_{it}$, $\ddot{x}_{it} = x_{it} - \overline{x}_i$, and $\ddot{\varepsilon}_{it} = \varepsilon_{it} - \overline{\varepsilon}_i$. The individual specific effect u_i has been removed by the demeaning of the equation. It can now be shown that Eq. (4.56) can be estimated by pooled OLS so that the fixed effects estimator is the pooled OLS estimator from the regression of $\ddot{q}_{it}$ on $\ddot{x}_{it}$ for $t = 1,2,\ldots,T$ and $i = 1,2,\ldots,N$. This estimator is unbiased under a strict assumption of exogeneity of the explanatory variables. Thus, the error ε_{it} should be uncorrelated to the explanatory variables across all time periods. The estimator allows arbitrary correlation between u_i and the explanatory variables in any time period. Therefore, explanatory variables that are constant over time for all i will drop out of the regression by the FE transformation. Additionally, one needs to assume that the errors ε_{it} are homoskedastic, i.e., all have the same variance and are serially uncorrelated across t. To sum up, despite the presence of an unobserved effect, the fixed effects estimator allows the estimation of partial effect of an explanatory variable on the outcome variable.

This is especially useful as many growth or convergence analysis context variables, e.g., the initial level of technology $A(0)$ cannot be measured adequately and is still assumed to affect growth and convergence.

Returning to the Solow model, Islam (1995) shows how the inclusion of a fixed effect can improve the results of convergence regressions. The starting point for his argument is the steady state per capita income as defined in Mankiw et al. (1992):

$$\log\left[\frac{Y(t)}{L(t)}\right] = \log A(0) + gt + \frac{\alpha}{1-\alpha}\log(s) - \frac{\alpha}{1-\alpha}\log\left(n+g+\delta\right) \tag{4.57}$$

One crucial assumption in this is that the rate of exogenous technological progress ln $A(0)$ + gt is identical for all countries. In a cross-section context t is fixed and gt is therefore a constant. $A(0)$ in contrast is assumed to reflect more than technology, namely, also resource endowments, climate, institutions, etc. and thus may differ between countries. Mankiw et al. therefore assume that

$$\log A(0) = \alpha + \varepsilon \tag{4.58}$$

with the constant α and ε a country-specific shock. Substituting this into the steady-state equation and including gt into the error term, they arrive at:

$$\log\left[\frac{Y(t)}{L(t)}\right] = a + \frac{\alpha}{1-\alpha}\log(s) - \frac{\alpha}{1-\alpha}\log\left(n+g+\delta\right) + \varepsilon \tag{4.59}$$

Thus, the country-specific technology term $A(0)$ is now included (partly) in the error term. This causes an omitted variable problem as it can hardly be assumed that the other components of the technology term such as resource endowments or institutions are uncorrelated with savings or population growth.

Islam (1995) argues that panel data allows better control for the technology term partly subsumed in ε. He approximates around the steady state to obtain the speed of convergence as in Eq. (4.22) and obtains:

$$\frac{\mathrm{d}\log\hat{y}\left(t\right)}{\mathrm{d}t} = \lambda[\log y^{*} - \log\hat{y}\left(t\right)] \tag{4.60}$$

where $\lambda = (g + n + \delta)(1 - \alpha)$, y^* corresponds to steady-state income per effective worker and $\hat{y}(t)$ is actual income at any time t. This implies income per effective worker at time t_2:

$$\log \hat{y}(t_2) = \left(1 - e^{-\lambda\tau}\right) \log \hat{y}^* + e^{-\lambda\tau} \log \hat{y}(t_1) \tag{4.61}$$

with $\tau = (t_2 - t_1)$. Subtracting $\ln\hat{y}(t_1)$ and rearranging gives:

$$\log \hat{y}(t_2) - \log \hat{y}(t_1) = \left(1 - \mathrm{e}^{-\lambda\tau}\right)(\log \hat{y}^* - \log \hat{y}(t_1)) \tag{4.62}$$

This represents the partial adjustment process taking place around the steady state. If $\hat{y}*$ is substituted in Eq. (4.62), it yields:

$$\begin{aligned}\log \hat{y}(t_2) - \log \hat{y}(t_1) = {} & \left(1 - \mathrm{e}^{-\lambda\tau}\right) \frac{\alpha}{1-\alpha} \log(s) \\ & - \left(1 - \mathrm{e}^{-\lambda\tau}\right) \frac{\alpha}{1-\alpha} \log(n + g + \delta) \\ & - \left(1 - \mathrm{e}^{-\lambda\tau}\right) \log \hat{y}(t_1)\end{aligned} \tag{4.63}$$

Note that the correlation between the $A(0)$ term and the observed included variables is not directly apparent as Eq. (4.61) is formulated in income per effective worker and in empirical applications income per capita is used. Thus reformulation in terms of income per capita is necessary. Income per effective labor is

$$\log \hat{y}(t) = \frac{Y(t)}{A(t)L(t)} = \frac{Y(t)}{L(t)A(t)\mathrm{e}^{gt}} \tag{4.64}$$

and thus

$$\log \hat{y}(t) = \log \frac{Y(t)}{L(t)} - \log A(0) - gt = \log y(t) - \log A(0) - gt \tag{4.65}$$

If $\log \hat{y}(t)$ is substituted for in Eq. (4.59) one gets

$$\begin{aligned}& \log y(t_2) - \log A(0) - gt_2 - (\log y(t_1) - \log A(0) - gt_1) \\ & \quad = \left(1 - \mathrm{e}^{-\lambda\tau}\right) \frac{\alpha}{1-\alpha} \log(s) - \left(1 - \mathrm{e}^{-\lambda\tau}\right) \frac{\alpha}{1-\alpha} \log(n + g + \delta) \\ & \qquad - \left(1 - \mathrm{e}^{-\lambda\tau}\right) \left(\log y(t_1) - \log A(0) - gt_1\right)\end{aligned} \tag{4.66}$$

After rearranging and canceling, finally Eq. (4.59) can be reformulated in terms of growth per effective labor, so that the common “growth initial level” equation is obtained

$$\log y(t_2) - \log y(t_1) = \left(1 - \mathrm{e}^{-\lambda\tau}\right)\frac{\alpha}{1-\alpha}\log(s) - \left(1 - \mathrm{e}^{-\lambda\tau}\right)\frac{\alpha}{1-\alpha}\log(n+g+\delta)$$
$$- \left(1 - \mathrm{e}^{-\lambda\tau}\right)\log y(t_1) + \left(1 - \mathrm{e}^{-\lambda\tau}\right)\log A(0) + g\left(t_2 - \mathrm{e}^{-\lambda\tau}t_1\right) \tag{4.67}$$

Collecting all log $y(t_1)$ terms on the right-hand side of the equation, income per effective worker at t_2 is given by

$$\log y(t_2) = \left(1 - \mathrm{e}^{-\lambda\tau}\right)\frac{\alpha}{1-\alpha}\log(s) - \left(1 - \mathrm{e}^{-\lambda\tau}\right)\frac{\alpha}{1-\alpha}\log(n+g+\delta)$$
$$+\mathrm{e}^{-\lambda\tau}\log y(t_1) + \left(1 - \mathrm{e}^{-\lambda\tau}\right)\log A(0) + g\left(t_2 - \mathrm{e}^{-\lambda\tau}t_1\right) \tag{4.68}$$

Islam (1995) assumes that s and n are constant between t_1 and t_2 for the individual cross sections.

From Eq. (4.68) it can be seen that $(1 - \mathrm{e}^{-\lambda\tau})\log A(0)$ can be interpreted as a time-invariant individual country effect in a dynamic panel data model. In panel notation this translates to

$$y_{it} = \phi y_{i,t-1} + \sum_{j=1}^{2}\beta_i x_{it}^{j} + \eta_t + \mu_i + \varepsilon_{it} \tag{4.69}$$

where $y_{it} = \log y(t_2)$, $y_{i,t-1} = \log y(t_1)$, $\phi = \mathrm{e}^{-\lambda\tau}$, $\beta_1 = \left(1 - \mathrm{e}^{-\lambda\tau}\right)\frac{\alpha}{1-\alpha}$, $\beta_2 = -\left(1 - \mathrm{e}^{-\lambda\tau}\right)\frac{\alpha}{1-\alpha}$, $x_{it}^1 = \log(s)$, $x_{it}^2 = \log(n+g+\delta)$, $\mu_i = (1 - \mathrm{e}^{-\lambda\tau})\log A(0)$, $\eta_t = g(t_2 - \mathrm{e}^{-\lambda t}t_1)$, and ε_{it} is the error term varying across countries and time periods with a mean equal to zero. In this setup the $(1 - \mathrm{e}^{-\lambda\tau})\log A(0)$ term represented by the country fixed effect is no longer correlated with the error term, leading to omitted variable problems and therefore biased estimators for the β. A random effects model specification is not appropriate, as this type of model assumes that no correlation exists between the exogenous variables and the individual effect, which is in this case the technology term log $A(0)$. In the present setup, however, a correlation between $A(0)$ and for example s and n can be assumed [see Islam (2003b)]. Generally, the panel approach has several benefits, including the fact that it uses information with regard to both cross section and longitudinal variance, it can help deal with the omitted variable bias and country-specific levels in initial technology can be modeled as country-specific effects (fixed effects) (Hemmer and Lorenz 2004). Convergence studies using panel methods have yielded higher estimated values for the speed of convergence λ (see, e.g., Islam 1995). However, the move from cross-section to panel methods also led to a change in the interpretation of the regression results. If the general understanding of convergence is that convergence is absolute, i.e., that different countries approach the same level of per capita income, the finding of faster but conditional convergence by means of panel methods makes “the obtained convergence hollower” (Islam 1995, p. 1162). Put differently: “There is probably little solace to be derived from finding that countries in the world are converging at a faster rate, when the point to which they are converging remain very different” (ibid).

Limitations of the Panel Approach

The treatment of unobserved heterogeneity by means of panel methods can bring substantial gains in robustness, but also has its costs (Durlauf et al. 2005). Fixed effects estimation cannot be used if variables are highly persistent. Also fixed effects estimation generally produces higher standard errors and in the case of a small time-series dimension T the parameter estimates become imprecise. The bias for small T will lead to the rate of convergence being overestimated. Moreover, dynamic panel models assume parameter homogeneity of the slope parameter. If this assumption is not met, slope parameters will vary across countries and the explanatory variables are serially correlated; then the error term will also be serially correlated, which leads to inconsistent estimates. For example, if it is wrongly assumed that $\beta_i = \beta$ for all $i = 1, \ldots, N$ for a given country there will be a component in the error process similar to $(\beta_i - \beta)\log y_{i,t-1}$, i.e., serial correlation in the errors. Another issue is the arbitrariness of the time periods which are selected over which to average the variables of interest. Panel studies often use 5-year periods to calculate averages of growth (and explanatory variables) which is less than in cross-sectional studies but still considerably longer than the yearly data often used in distributional approaches and time-series approaches. Durlauf et al. (2005) argue that there is no reason why observations should be averages over 5 or 10 years and that the time periods over which aggregation takes place is also random. Islam (2003b), however, argues that this may not be too short to study growth. When several 5-year periods are combined to produce the regression estimates, the effects of cutoff years are likely to get canceled out. He shows that the results from a pooled estimation on the basis of 5-year span data are very similar to results obtained from a single cross section spanning the whole period under consideration (Islam 1995).

4.2.2.2 A General Overview of the Limitations of Analysis of β-convergence

Besides the issues mentioned above, other problems arising with β-convergence in general include robustness with respect to choice of control variables, the relationship between β-convergence and economic divergence, endogeneity issues, measurement error, and linear approximation (Durlauf et al. 2005). Each will be discussed briefly in the following section.

Regression results have not always proven to be robust with regard to the choice of control variables as a “growth regression industry” has led to the addition of an increasing number of variables to the baseline Solow specification (Durlauf et al. 2005, p. 587).

The steady state in a conditional β-convergence context depends on more variables than those four included in the basic Solow specification, namely, n, g, δ, and s. The result of this was that depending on the variables included, variants of the convergence equation could be specified revealing convergence while others revealed divergence. However, Durlauf et al. (2005, p. 587) argue that after efforts to address model uncertainty "the evidence for conditional β-convergence appears to be robust with respect to choice of controls."

Another problem arising concerns the relationship between β-convergence and economic convergence as defined in Eq. (4.43) or variations of it. Durlauf et al. (2005) argue that literature on the β-convergence lacks convergence tests that are capable of discriminating between convergent economic models and a set of non-converging alternatives. They explain that while $\beta < 0$ is an implication of the baseline convergent model in the literature it might also be possible that $\beta < 0$ is also consistent with non-converging growth models that are economically interesting. For instance, the model of Azariadis and Drazen (1990) displays a discontinuity in the aggregate production function. This is evident in that the steady-state behavior of an economy depends on whether the economy starts below or above a certain threshold. In this case two thresholds are modeled, but theoretically any number of thresholds is possible. This model exhibits no economic convergence as long as there are two or more steady states. However, with this model it is possible that the empirical representation of its cross-country regression function yields a negative β, even if the country sample includes countries associated with different steady states. This means that while the theoretical model does not display convergence if there is more than one steady state present, the data generated by economies that may be described by this model may exhibit convergence measured by the coefficient β. This might be the case if low-income countries tend to start below their steady states and high-income countries above theirs. This is not necessarily true empirically; however, it can be shown that statistical convergence need not go hand in hand with economic convergence. Put differently, a negative β may be consistent with economic non-convergence. Studies exist suggesting that multiple steady states fit the cross-country data better than the Solow model, e.g., Durlauf and Johnson (1995). Also there are studies implying that the β might not be constant across economies, e.g., Liu and Stengos (1999). Findings like these imply that observed growth patterns are compatible with permanent income differences, i.e., non-convergence between economies with similarities in terms of population growth, savings rates, and access to identical technologies.

Endogeneity of the explanatory regressors in growth regressions is another criticism with regard to the examination of β-convergence. If endogeneity is present, estimates of the regression parameters may not be consistent. Instrumental variable approaches and panel methods with growth measured in 5-year intervals have been used to remedy this problem, but, as Durlauf et al. (2005) argue, still require considerable work.

Measurement error occurs because growth γ_{it} is measured with positive error when $\log y_{i,0}$ is measured with negative error and vice versa. In other words, if the initial income $\log y_{i,0}$ is measured smaller than it actually is, the growth rate γ_{it} will be measured larger than reality. Therefore, there tends to be a negative correlation between the measured values even if there is no correlation between the true values (Durlauf et al. 2005). If measurement error is present, the regression results will tend to be biased in line with the β-convergence hypothesis, as Abramovitz (1986) and Baumol (1986), for example, point out.

Regarding the last issue, the effects of linear approximation, Durlauf et al. (2005) claim that the linear approximation used to estimate β-convergence is "reasonably accurate" and that nonlinearities in the growth process do not reflect the inadequacy of the linear approximation.

Hemmer and Lorenz (2004) argue that shortcomings in the analysis of β-convergence as well as the debate on Galton's fallacy and the conclusion that β-convergence does not necessarily lead to a diminishing of the dispersion of per capita incomes (or another variable of interest) showed that the usefulness of the convergence concept depends strongly on the type of question asked. They explain that in an optimal case the concept of conditional β-convergence—which implies convergence of the growth rates and not of the absolute levels—can provide information on speed of convergence; thus how fast adjustment can be expected under specified assumptions. For questions of a more descriptive type such as whether there is a decrease in the variation of per capita incomes over time, the concept of σ-convergence can be used. The concept of σ-convergence does not allow an insight into the actual mobility patterns within the international income distribution. To answer the question of whether the per capita incomes of poorer and richer countries actually assimilate, time-series approaches have to be chosen. One of the time-series approaches to convergence analysis will be discussed in the next section.

4.2.3 Time-Series Approaches to Convergence

Proponents of time-series approaches have additional criticisms regarding the issues mentioned above with regard to cross-section regressions. They argue that averaging the growth rates of per capita income or labor productivity over long periods of time is only a valid procedure if permanent income development is characterized by a smooth trend, and not influenced by random shocks. If this is not the case, a regression of the average growth rates can lead to wrong conclusions being formed. In extreme cases, this can be seen if the development of per capita incomes of individual countries over time is interpreted as a random walk process. As the random walk does not possess a finite variance the OLS estimator is not consistent, and the problem of a spurious regression may occur (Hemmer and Lorenz 2004). Quah (1996a) argues that the 2 % rate of convergence found in empirical studies may be the result of a unit-root process in the data. If a unit root is present in the data of the convergence regression "all that the investigator could hope to uncover is the unit coefficient" of the data generating process (Quah 1996a, p. 1358). In addition, Quah conducted a Monte Carlo simulation which suggested that the results of β-convergence are a statistical artifact. Evans (1996) explains that drawing inference from cross-section approaches may only be reliable under certain "highly implausible" conditions. These conditions are that the explanatory variables included in the regression can control for all variation in either mean levels or growth rates, that the time series of the countries examined are first-order autoregressive processes, and that the error terms of the regressions are serially uncorrelated. He argues that particularly due to international trade in goods the third assumption of uncorrelated errors is probably invalid. Consequently, "valid inference is difficult if not impossible" (Evans 1996, p. 1031). Another critique relates to the fact that the averaging of growth rates over long periods of time "wastes" valuable time-series information, and the results of such cross-section regressions do not mirror the actual growth dynamics of economies (Hemmer and Lorenz 2004). As a result of these issues authors like Evans (1996) suggest a time-series approach by means of unit roots or cointegration analysis.

The relevance of the unit-root analysis for growth or convergence research will be discussed next, as unit-root analyses are an essential part of empirical analysis of convergence (Hemmer and Lorenz 2004). The analysis by Nelson and Plosser (1982) provided the first evidence for a stochastic trend in per capita incomes and other macroeconomic variables. They suggest that per capita incomes are not trend stationary but rather difference stationary. As prior events have a permanent effect on present realizations, per capita incomes are thus path dependent in the sense that history matters. Empirically, this is confirmed by testing the time series for the existence of unit roots. If income displays a stochastic trend the variance will increase indefinitely over time and there will be no reversion towards a common trend. In the context of a convergence analysis this raises the question of how unit roots and β-convergence can be reconciled, as the theoretical implications of the divergence of unit-root processes stand in contrast to the findings of β-convergence. One possible explanation is that the contemporary output is cointegrated with the steady-state output and/or that the economies displaying conditional convergence follow a common stochastic trend.

4.2.3.1 Convergence Definitions in Time Series

In contrast to cross-sectional analysis, time-series analysis of convergence "places the convergence hypothesis in an explicitly dynamic and stochastic environment" (Bernard and Durlauf 1995, p. 100). In order to examine convergence in a time-series context a suitable definition of convergence in time-series terminology is required (Hemmer and Lorenz 2004). Time-series analysis focuses on growth dynamics in the very long run; alternative growth determinants remain an object of cross-section regressions. In contrast to the methods used by regression approaches, convergence in a time-series setting is examined by means of a long-run forecast of per capita incomes, which depends upon initial conditions. This is why this concept of convergence is also called *time-series forecast convergence*. There are two types of definitions: the "strong" definition identifies convergence if the differences in per capita incomes between all pairs of countries are transitory, and the long-run forecast converges towards zero as the forecasting horizon increases.[2] This can be shown formally:

$$\lim_{k \to \infty} E\left(y_{1,t+k} - y_{j,t+k} \middle| \eta_t\right) = 0 \tag{4.70}$$

where η is the level of information of the respective period.

The "weak" time-series forecast convergence definition only requires the long-run forecast of the differences between each pair of countries $(1,j)$ to approach a finite constant. The countries follow a common trend if their conditional long-run forecasts are proportional at time t. This weak time-series forecast convergence occurs if the per capita levels of two countries are cointegrated. This can be formally described by

$$\lim_{k \to \infty} E\left(y_{1,t+k} - \theta \overline{y}_{t+k} \middle| \eta_t\right) = 0 \tag{4.71}$$

with $\overline{y}_t = \left[y_{2,t}, y_{3,t}, \ldots, y_{p,t}\right]$ and θ a proportionality factor. This weak form of convergence can be empirically tested, for example, undertaken by Evans and Karras (1996) and Evans (1998). Their approach will be discussed later. Generally, time-series analyses of convergence are not explicitly tied to particular growth theories and start mostly from reduced form equations of the output process. These can, however, as argued by Islam (2003b), be linked to growth theories. Before the more technical aspects of the time-series approach of Evans and Karras (1996) and Evans (1998) are examined the difference between the time-series forecast convergence and β- and σ-convergence will be evaluated.

Hemmer and Lorenz (2004) explain that the strong version of the time-series convergence concept implies both β-convergence and σ-convergence. The time-series concept however features a stricter notion of convergence than those based on cross-section regressions or cross-section variance, because the latter only require that the differences of per capita income tend to decrease over time, i.e., convergence in the sense of catching-up. Catching-up can be defined in terms of time-series convergence as a decreasing of the expected value of the differences between the per capita incomes of two countries over time. It is however not usually tested in the context of time-series examinations. Both concepts of time-series forecast convergence can be a useful supplement to the concepts of β- and σ-convergence.

Bernard and Durlauf (1996) state that time-series approaches have yielded different results than cross-section analyses when applied to output series. Cross-section convergence tests generally tend to reject the null of no convergence for the advanced economies (Baumol 1986; Dowrick and Nguyen 1989), the US regions

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[2] For more details on the strong version of time series convergence, see Hemmer and Lorenz (2004).

(Barro and Sala-i-Martin 1991, 1992), or large international cross sections when controlling for example for population growth or savings (Barro 1991; Mankiw et al. 1992). Early time-series tests, for instance, Bernard and Durlauf (1995), generally have accepted the null of no convergence.

It is important to note the data properties required for the conduction of time-series tests of convergence. It is assumed that the data is generated by economies near their limiting distribution, i.e., steady-state distribution. If economies which cannot be assumed to be near their steady state, the sample moments of the data may not accurately approximate the limiting population moments. Put differently, "time series tests may have poor power properties when applied to data from economies in transitions" (Bernard and Durlauf 1996, p. 171). Cross-section tests on the other hand assume that the countries, i.e., the data they generate, are in transition towards a limiting distribution. Therefore, cross-section tests may be more appropriate in a context of transition (Bernard and Durlauf 1996).

Time-series analysis has been used to examine convergence within economic units towards its own steady state, but time-series convergence analysis has also been used to examine convergence across economies (Islam 2003b), as for instance in Evans and Karras (1996) and Evans (1998) who conducted a unit-root analysis in a pooled cross-section framework, i.e., a macro panel setting. In this dissertation this definition of convergence is applied in the time-series analysis of convergence. This approach will therefore be discussed in greater detail.

4.2.3.2 A Panel Unit-Root Approach to Convergence in Time Series

Evans and Karras (1996) and Evans (1998) discuss a strategy analyzing convergence in a macro panel. Neoclassical growth models typically imply the existence of a unique balanced growth path for variables such as per capita income and assume that deviations from that growth path are eventually eliminated so that initial values of per capita income have no effect on their long-run levels. The common growth paths lie in parallel as the economies are assumed to have access to a common body of technological knowledge. Consequently, state variables such as per capita income, capital, or population differ by constant amounts. This difference can then be represented for each economy n by

$$\lim_{t \to \infty} \left(y_{i,t+\mathrm{k}} - a_{t+\mathrm{k}} \right) = \omega_n \tag{4.72}$$

when $y_{i,t}$ is the log of per capita output of economy n at common, constant international prices during period t, a_t is a common trend followed by all economies, and ω_n is a parameter. a_t can be interpreted as a logarithm of Harrod-neutral technology available in the economies. ω_n determines the level of the balanced growth path followed by economy n. Only in the case of unconditional convergence, when all economies share the same structural characteristics should ω equal zero. Otherwise, in the case of conditional convergence it will be nonzero and differing for all or some countries N.

In contrast, endogenous growth models imply that initial conditions matter and that the long-run outcome of for example per capita income is affected by their initial values. Therefore, $\lim_{t\to\infty}\left(y_{i,t+\mathrm{k}}-a_{t+\mathrm{k}}\right)$ moves with $y_{i,t}-a_t$. Thus, initial differences between income and the common trend will remain.

Convergence between the economies 1,2,. . .,N then occurs if, and only if, for $n=1,2,\ldots,N$ a common trend a_t and finite parameters $\omega_1, \omega_2, \ldots, \omega_N$ exist such that

$$\lim_{t\to\infty} E_t\left(y_{i,t+\mathrm{k}}-a_{t+\mathrm{k}}\right)=\omega_n \tag{4.73}$$

As a_t is unobservable, transformations are required to generate an equation only with observables. To obtain an observable measure for the common trend they average over the N members and obtain:

$$\lim_{t\to\infty} E_t\left(y_{i,t+\mathrm{k}}-\overline{y}_{t+\mathrm{k}}\right)=\omega_n \tag{4.74}$$

with

$$\overline{y}_t\equiv\sum_{n=1}^{N}\frac{y_{i,t}}{N} \tag{4.75}$$

They measure the common trend a_t so that it corresponds to $\overline{y}_t$. Thus, the deviations of $y_{1,t+k}, y_{2,t+\mathrm{k}}, \ldots, y_{N,t+\mathrm{k}}$ from their cross-economy average $\overline{y}_t$ can be expected to approach constant values as i approaches infinity. Equation (4.75), however, only holds if $y_{i,t}-\overline{y}_t$ is stationary with an unconditional mean vector ω_n for $n=1,2,\ldots,N$. If $y_{i,t}-\overline{y}_t$ is not stationary no constant integer μ_n can be found and thus convergence does not occur. Hence, the economies 1,2,. . .,N converge if, and only if, every y_{it} is nonstationary and every $y_{it}-\overline{y}_t$ is stationary.

This can be shown in a pooled cross-country setup (Evans 1998). Here, pairwise convergence for the pair of countries i and j occurs if the difference $y_{jt}-y_{it}$ is stationary. If $y_{jt}-y_{it}$ is stationary y_{jt} and y_{it} are cointegrated and exhibit a nonzero mean. Convergence holds for a larger group of countries because if the difference $y_{it}-y_{jt}$ is stationary for all pairs of countries i and j then it follows from

$$y_{it}-\overline{y}_t=\frac{1}{N}\sum_{m=1}^{N}\left(y_{it}-y_{jt}\right) \tag{4.76}$$

that $y_{it}-y_{jt}$ is stationary for all i. And vice versa, if $y_{it}-\overline{y}_t$ is stationary for all i, it follows that $y_{it}-y_{jt}$ is stationary for all pairs (i,j) because

$$y_{it} - y_{jt} = (y_{it} - \overline{y}_t) - \left(y_{jt} - \overline{y}_t\right) \tag{4.77}$$

If the y's of some countries are not cointegrated with the y's of other countries, it follows for all n that y_{it} is not cointegrated with $\overline{y}_t$ and hence $y_{it} - \overline{y}_t$ contains a unit root and is thus only difference stationary. This would imply no convergence.

Evans and Karras (1996) continue arguing that if the data is generated by

$$\lambda_n(L)(y_{it} - \overline{y}_t) = \delta_i + \varepsilon_{it} \tag{4.78}$$

where $\lambda_i(L) \equiv -\lambda_{i1}(L)$, L being the lag operator, and $-\lambda_{i1}$ are parameters lying on the interval [0,1] and differing across economies, Eq. (4.78) can be rewritten so that

$$\Delta(y_{it} - \overline{y}_t) = \delta_i + \rho_i\left(y_{i,t-1} - \overline{y}_{t-1}\right) + \sum_{i=1}^{p} \varphi_{i,k}\Delta\left(y_{i,t-k} - \overline{y}_{t-k}\right) + \varepsilon_{it} \tag{4.79}$$

This is essentially an Augmented Dickey–Fuller regression from which inferences about the presence or absence of convergence can be drawn. If $\rho_i = 0$ the process contains a unit root and the economies thus display divergence. If ρ_i is negative no unit root is present and the economies converge. It is assumed that the errors become uncorrelated across economies as N approaches infinity. Summing up, $y_{it} - \overline{y}_t$ is stationary if $\rho_i < 0$ and nonstationary if $\rho_i = 0$. In the present context of the Augmented Dickey–Fuller regression the stationarity or non-stationarity of $y_{it} - \overline{y}_t$ can thus be evaluated by examining whether the autoregressive parameter ρ_i is zero or not. This in turn corresponds to the null hypothesis in unit-root tests [see also Pedroni and Yao (2006)]. In Eq. (4.79), the δ_i represents fixed effects which vary between countries. They describe the individual country's average sample difference from the group mean $(y_{it} - \overline{y}_t)$ and are allowed to vary by country. While the autoregressive parameter ρ_i is used to determine presence or absence of convergence, the lagged difference terms capture higher order serial correlation in the time-series process for income differentials with the number of lags K_n chosen such that the remaining error terms ε_{it} are serially uncorrelated. In this specification the hypothesis to be tested takes the form

$$\mathrm{H}_0 : \rho_i = 0 \;\text{ for all } i$$

against the alternative

$$\mathrm{H}_1 : \rho_i < 0 \;\text{ for some } i$$

Rejection of the null against the alternative implies that at least some subset of panel members are converging towards each other. A failure to reject the null implies that there is no subset of panel members converging towards each other. These hypotheses can be tested by means of panel unit-root tests, as undertaken by for instance Pedroni and Yao (2006). The empirical strategy of this dissertation follows their approach, using unit-root tests to test for convergence. Two types of panel unit-root (PUR) tests are employed: the panel unit-root test by Im et al. (2003) and by Maddala and Wu (1999) and Choi (2001).

4.2.3.3 Panel Unit-Root Tests

Recent research undertaken in time-series econometrics and panel data analysis have focused on the unit-root and cointegration properties of variables spanning a relatively long time period and a large number of cross-section units, such as countries or regions.[3] The primary use of these panel datasets has so far been to test the output convergence and the purchasing power hypothesis. These panels are characterized by relatively large time (T) and cross-section (N) dimensions. In this context, large N or T means fewer than 100 but more than 10 entities or time periods. The motivation for the application of panel unit-root tests is to gain statistical power and to improve the rather weak strength of the unit-root tests in single time series. An example is the application of the so-called first-generation panel unit-root tests to real exchange rates, output, and inflation. Breitung and Pesaran argue that while the Augmented Dickey–Fuller test typically was unable to reject the hypothesis that the real exchange rate is nonstationary, panel unit-root tests for a collection of industrialized countries could determine that real exchange rates are indeed stationary, thus supporting the purchasing power hypothesis. However, several additional complications arise when testing the unit-root and cointegration hypothesis. Firstly, the use of panel data leads to a substantial amount of unobserved heterogeneity, which as a result causes the parameters to become cross-section specific. Secondly, in many empirical applications, and also when applied to convergence, the assumption that cross-section units are independent is implausible. In a convergence context this would imply that the output of one country is not dependent on the output of another country. A second generation of PUR tests has been developed to overcome this difficulty, e.g., Pesaran (2007). Third, the interpretation of the test in the case of a rejection of the unit root can be difficult as a rejection implies that "some panels are stationary." However, no indication is provided as to the size of the fraction or identity of the stationary cross-section units. Fourth, if unobserved, common factors integrated of order 1 [$I(1)$] affect some or all variables in the panel. It is possible that not only cointegration between variables across groups is present (cross-section cointegration) but also that variables are cointegrated within groups, i.e., the variable to be examined may be cointegrated with some other unobserved, common variable. Finally, as the sampling design includes a time and a cross-section dimension the asymptotic theory is considerably more complicated. For instance, the application of a standard Dickey–Fuller test to a panel introduces a bias which is not present in the univariate case. Additionally, the limit theory for panel unit-root tests has to consider the relationship between increasing numbers of time periods and cross-sectional units.

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[3] For the following, see Breitung and Pesaran (2008).

Next, the basic model for panel unit-root tests will be described as well as the first-generation panel unit-root tests.

4.2.3.4 The Basic Model for Panel Unit-Root Tests

It is assumed that the time series $\{y_{i0}, \ldots, y_{iT}\}$ on the cross-section units $i = 1,2,\ldots, N$ are generated for each i by a simple first-order autoregressive, AR(1), process represented by

$$\lambda(L)y_t = (1 - \alpha_i)\mu_i + \varepsilon_i \text{ with } \lambda(L) = I - \alpha_i L \tag{4.80}$$

$$y_{it} = (1 - \alpha_i)\mu_i + \alpha_i y_{\mathrm{i},t-1} + \varepsilon_{it} \tag{4.81}$$

where the initial values y_{i0} are given and the errors are identically independently distributed (i.i.d.) across i and t. This process can also be written as a simple Dickey–Fuller (DF) regression of the form

$$\Delta y_{it} = -\rho_i\mu_i + \rho_i y_{i,t-1} + \varepsilon_{it} \tag{4.82}$$

where $\Delta y_{it} = y_{i,t} - y_{i,t-1}$ and $\rho_i = \alpha_1 - 1$. It is also possible to write Eqs. (4.81) and (4.82) in mean deviation form, as for instance in Evans (1998) so that:

$$\widetilde{y}_{it} = \alpha_i\widetilde{y}_{i,t-1} + \varepsilon_{it} \text{ with } \widetilde{y}_{it} = y_{it} - \overline{y}_i \tag{4.83}$$

The Dickey–Fuller regression in $\widetilde{y}_{it}$ is then given by

$$\Delta\widetilde{y}_{it} = \rho_i\widetilde{y}_{i,t-1} + \varepsilon_{it} \tag{4.84}$$

The null hypothesis of the Dickey–Fuller unit-root test is

$$\mathrm{H}_0 : \rho_1 = \cdots = \rho_N = 0 \tag{4.85}$$

which implies that all time-series are independent random walks. Two alternative hypotheses can be considered:

$$\mathrm{H}_{1\mathrm{a}} : \rho_1 = \cdots = \rho_N \equiv \rho \text{ and } \rho < 0 \tag{4.86}$$

$$\mathrm{H}_{1\mathrm{b}} : \rho_1 < 0, \ldots \phi_{N0} < 0, N_0 \leq N \tag{4.87}$$

$\mathrm{H}_{1\mathrm{a}}$ is called the homogeneous alternative and assumes that the autoregressive parameter is identical for all cross-section units, like for instance in the Levin et al. (2002) test. $\mathrm{H}_{1\mathrm{b}}$ is called the heterogeneous alternative assuming that a number N_0 of the N panel units $(0 < N_0 \leq N)$ are stationary with individual specific autoregressive coefficients, as for instance in the test by Im et al. (2003). Consistency of the test requires the assumption that $N_0/N \to \kappa > 0$ as $N \to \infty$; this translates to the requirement that the fraction of individual processes that are stationary is nonzero. Depending on the alternative hypothesis, different panel testing procedures can be applied. When testing for the first alternative H_{1a} the test statistic pools the observations across the different cross-section units and then constructs a pooled statistic. The tests for the second alternative H_{1b} use the test statistics for the individual cross-section units directly. The standardized simple averages of the underlying individual statistics or their suitable transformations such as rejection probabilities are used to calculate the overall test statistic. Note that despite the differences in the formulation of the alternative hypotheses both tests can be consistent against both types of alternatives. Also, as already mentioned, interpretation of the test outcomes faces the problem that a rejection of the null hypothesis implies only that a significant fraction of the AR(1) processes in the panel do not contain unit roots. Procedures for the Im, Pesaran, and Shin test and for Fisher-type tests such as Choi (2001) and Maddala and Wu (1999) will be discussed next.

4.2.3.5 The Im, Pesaran, and Shin Test

The Im et al. (2003) (IPS) test is a so-called group mean "between dimension" test (Pedroni and Yao 2006, p. 304). It assumes the parameters of interest are heterogeneous across panel members, corresponding to H_{1b} from above. Also, all other parameters and dynamics can be member specific. The test calculates a group mean estimate of the individual t-statistics, by combining the evidence on the unit-root hypothesis from unit-root tests on the panel members.

Im et al. (2003) test the following hypothesis:

$$H_0 : \rho_i = 0 \text{ for all } i \tag{4.88}$$

$$H_1 : \begin{cases} \rho_i < 0 \text{ for } i = 1, 2, \ldots, N_1 \\ \rho_i = 0 \ \text{ for } i = N_{1+1}, \ldots, N \end{cases} \tag{4.89}$$

where the fraction of stationary time series is nonzero.

The Im, Pesaran, and Shin (IPS) test proceeds as follows: Firstly, as before the ADF regression is conducted for each member of the panel. Again first differences or demeaned first differences are used. Member-specific fixed effects or time trends can be included in the ADF regression. Next, the t-statistics for the H_0: $\phi_1 = 0$ for each member of the panel is computed. This in turn is used to construct an average of the individual t-statistics from the ADF regression (also called the group mean value) of the t-statistics for the panel $\bar{t}$. As the distribution of the individual ADF t-statistics is not centered around zero under the unit-root null hypothesis, it is necessary to adjust for this in order to ensure that as N grows large the distribution of the $\bar{t}$-statistic does not diverge under the null hypothesis (Pedroni and Yao 2006). Therefore, finally, the $\bar{t}$-statistic is adjusted so that it is distributed standard normally under the null hypothesis and will diverge to negative infinity under the alternative hypothesis.

In a context of convergence the heterogeneity of the parameter of interest implies that the panel members' convergence rate may differ, which is more likely to be found in reality. Also, over-fitting this test in terms of lag selection is less harmful for the inference of the test than under-fitting it and again a trade-off between power and size is involved.

Im et al. (2003, p. 73) point out that special care is warranted when interpreting this test. As the alternative hypothesis is heterogeneous (see Eq. 4.89) "rejection of the null hypothesis does not necessarily imply that the unit-root null is rejected for all i, but only that the null hypothesis is rejected for $N_1 < N$, members of the group such that $N \rightarrow \infty$, $N_0/N \rightarrow \kappa > 0$." In other words, the unit-root null may only be rejected for a fraction of the sample and a few series can influence the result. In terms of convergence analysis this implies that rejection of the unit-root null does not mean that all countries considered are converging, but that at least some subset of them is converging. Also the test does not provide guidance with regard to the number or identity of countries for which the null hypothesis is rejected. Other issues with the IPS test concern the assumption of independence across the panel members, and that it requires a balanced panel to be estimated. Also, the IPS test assumes that the time series under consideration are independent across n. However, in many macroeconomic applications, like purchasing power parity or output convergence, the time series of the countries examined may be contemporaneously correlated (Breitung and Pesaran 2008).[4]

4.2.3.6 The Maddala and Wu or Choi Test

Maddala and Wu (1999) and Choi (2001) independently suggested another test against the heterogeneous alternative H_{1b} based on the p-values of the individual statistics. As with the IPS test this test also allows different deterministic trends and lag order for each panel member (Breitung and Pesaran 2008). This type of test is sometimes also called Fisher-type tests, as they pool the significance values of the individual ADF tests of the panel members as suggested by Fisher (1970, first published in 1932) and base their test statistic on the Fisher or Person lambda statistic. Specifically, the ADF regression is estimated for each member of the panel. Next, the t-statistic under the null hypothesis is computed as well as the corresponding p-value π_i. The p-values are then used to calculate the test statistic. Maddala and Wu use the test statistic defined by

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[4] An overview of the development of methods to treat cross-section dependence in large panels can also be found in Breitung and Persaran (2008, pp. 295–297). Reasons for cross-section dependence include omitted observed common factors, spatial spillover effects, unobserved common factors, and general residual interdependence.

$$P = -2\sum_{i=1}^{N} \log \pi_i \tag{4.90}$$

It is also called the inverse chi-square test because $-\ 2 \log \pi_n$ has a chi-square distribution with $2N$ degrees of freedom.

Choi (2001) proposes this statistic as well as two other statistics, the Z and the L-statistic. The Z-statistic is defined as

$$Z = \frac{1}{\sqrt{N}}\sum_{i=1}^{N} \phi^{-1}(\pi_i) \tag{4.91}$$

and is called the inverse normal test, because $0 \le \rho_i \le 1,\ \ \phi^{-\ 1}\pi_n$ is a standard normal random variable.

The L-statistic, also called logit test, is defined as

$$L = \sum_{i=1}^{N} \log\left(\frac{\pi_i}{1-\pi_i}\right) \tag{4.92}$$

All three tests are consistent against the alternative hypothesis and the following decision rules are given: For each test reject the null hypothesis against the alternative in the case of finite N at the significance level α when the following inequalities hold:

$$P > c_{\mathrm{pa}}$$

where c_{pa} is from the upper tail of the chi-square distribution with $2N$ degrees of freedom.

$$Z < c_{\mathrm{za}}$$

where c_{za} is from the lower tail of the standard normal distribution, and

$$L < c_{\mathrm{la}}$$

where c_{la} is from the lower tail of the t-distribution with $5N + 4$ degrees of freedom. For large N ($>$100) the transformed test statistic has a standard normal limiting distribution.

In contrast to the other tests discussed, these Fisher-type tests can also be used in unbalanced panels and they allow different lag lengths in the individual ADF regressions. Moreover, these tests can theoretically be based on any unit-root test. The Dickey–Fuller and the Perron version are implemented in the statistical software package Stata®. A disadvantage of the Fisher-type tests is that the p-values are not readily available and have to be obtained by simulation.

4.2.3.7 A Comparison of the Tests and Their Limitations

Choi and Maddala and Wu argue that Fisher-type tests are superior to the IPS and LLC tests. Choi indicates that of the different Fisher types: P, L, and Z, the Z-test is the best. Another advantage in comparison to other tests is that it does not pose the "all or nothing" question. In other words, it allows testing of whether some series may contain unit roots vs. some series are stationary. Testing whether all series are stationary vs. all series are nonstationary is often very restrictive. For the Fisher-type tests the same issues with regard to interpretation arise as for the IPS test. Rejection of the unit-root null does not imply that all series are stationary, but only that a fraction of them is stationary. The following extreme case can illustrate the problem: With $N = 10$, suppose that the p-values for the 10 individual unit-root tests are close to 0.5 for nine series and 0.000001 for the last series. The chi-square test statistic will be very high and reject the unit-root null. However, for 9 out of the 10 series the unit-root null is not rejected and the overall rejection is based on a single, strong rejection. A similar outcome can be expected with the IPS test as well.

Other problems arise when errors are cross-correlated; the test statistic will not be distributed as described earlier but be subject to substantial size distortions. In this case bootstrapping may be necessary to derive the empirical distribution of the test statistics. Furthermore, the Fisher-type tests also assume independence of the time-series data; however, when there is cross-sectional dependence present this will pose problems for the interpretation and validity of the tests.

A comparison of the IPS and the Fisher-type tests can be found in Choi (2001), Maddala and Wu (1999), and Maddala (1999). The IPS and Fisher-type tests both combine information from a set of independent tests of the same hypothesis. Their manner of combination differs however, as the IPS combines the t-statistics and the Fisher-type tests combine the significance levels. The IPS and the Fisher-type tests cannot account for contemporaneous correlation between the different time series. This poses a problem in many macroeconomic applications using country data, because cross-section dependence may arise, for example, due to omitted observed common factors or spatial spillover effects (Breitung and Pesaran 2008). Regarding the comparability of the tests, the IPS and the Fisher-type tests are directly comparable, as they both combine significance of different independent tests. They differ in the sense that the IPS test is asymptotic and the Fisher tests are exact. The use of significance levels or test statistics both bears problems and neither the IPS nor the Fisher-type tests remain strictly valid if contemporaneous correlation is present. The result of this is correlations between the individual test statistics.

Generally, Islam (2003b) argues that problems with the time-series approach to convergence analysis can arise as the source of the rejection of the unit-root null is not always clear. For instance when the time series are demeaned, deviations from the sample average are examined: If the time series of one economy contains a unit root, the average will also contain one; other than for the country with the unit root all deviations will also display unit roots. Durlauf et al. (2005) mention issues arising relating to the validity of unit-root tests in the presence of structural breaks and long memory characteristics of the data. Failure to account for structural breaks may lead to spurious evidence in favor of the null of non-convergence. Also unit-root tests may perform badly if the data generating process exhibits long memory, i.e., shocks die out at a hyperbolic rather than a geometric rate. Strauss and Yigit (2003) argue that if the assumption of i.i.d. errors is violated this leads to size distortions in the test statistics and a demeaning of the series often cannot eliminate this problem.

Despite the limitations of the time-series approach to convergence and the need for further development of the methods, its application can contribute to a better understanding of convergence patterns. It allows the testing of a specific hypothesis, greater freedom in terms of parameter heterogeneity, as well as the possibility of exploiting the full potential of the available time-series data.

A second approach to convergence, the so-called distributional approach, is concerned with the behavior of the cross-section distribution of income (or any other variable of interest). Within this field the analysis of σ-convergence and later a broader examination of the evolution of the global income distribution can be distinguished. In this dissertation only σ-convergence is analyzed and its theoretical basics will therefore be briefly discussed. For an overview of the study of the evolution of the global income distribution, see, for example, Durlauf et al. (2005) or Islam (2003b).

4.2.4 σ-convergence

σ-convergence forms part of the distribution approach to examining convergence. It is concerned with the cross-section distribution of income (or another variable of interest) in levels. σ-convergence and distributional approaches are not concerned with analyzing the relative locations within the distribution, i.e., whether poor countries can be expected to catch up with rich countries. Analysis of the development of the cross-section dispersion of log $y_{i,t}$ has been a focus of the empirical literature on cross-country distribution of income. Two measures have been proposed to examine this: the standard deviation of the log of per capita income and the coefficient of variation of per capital income (Barro and Sala-i-Martin 1992; de la Fuente 1997; Dalgaard and Vastrup 2001). The standard deviation (SD) s is the square root of the variance and is calculated as follows:

$$s = \sqrt{\frac{1}{n}\sum (x_1 - \bar{x})^2} \tag{4.93}$$

The coefficient of variation (CV) υ corresponds to the standard deviation normalized by the mean

$$\upsilon = \frac{s}{\bar{x}}. \tag{4.94}$$

The SD, in contrast, is measured in the same units as the observations; the coefficient of variation is a standardized measure. σ-convergence holds between t and $t + T$ if

$$s_{\log y,t} - s_{\log y,t+T} > 0 \tag{4.95}$$

or

$$\upsilon_{y,t} - \upsilon_{y,t+T} > 0 \tag{4.96}$$

where $s_{\log\, y,t}$ denotes the SD of log $y_{i,t}$ across i and $\upsilon_{\mathrm{y,t}}$ denotes the coefficient of variation across I at t and $t + T$, respectively. This definition formalizes the idea that income differences are transitory and considers the dispersion of these differences over time. It can be shown that a negative β does not automatically guarantee σ-convergence, i.e., a falling dispersion. Thus, β-convergence is not sufficient for σ-convergence. However, increasing cross-sectional dispersion can go hand in hand with β-convergence. Sala-i-Martin (1996) graphically illustrates three possible patterns of the relationship between σ- and β-convergence (see Fig. 4.6).

The first tile shows a pattern where neither β- nor σ-convergence occurs. In the second tile β-convergence occurs and thus facilitates σ-convergence. In the last case, the poorer country B is able to catch up, thus β-convergence occurs. However, due to B having grown faster than A, it has overtaken A at $t + T$ so that the distance between the two countries is the same as in t. Therefore, no σ-convergence took place.

Empirical evidence regarding σ-convergence is mixed and dependent on the country sample. Islam (2003b) summarizes that for a global sample, the evidence generally indicates a rise in variance, i.e., σ-divergence. He also explains that it has been argued that the evolution of the entire shape of the distribution should be given more attention. This line of research is concerned with the individual positions of countries within the distribution change over time. A major researcher in this area has been Quah (e.g., Quah 1993, 1996a, b, 1997). The distribution approach will however not be elaborated in more detail in this dissertation. Excellent overviews of the distribution approach can be found for example in Durlauf et al. (2005) or Islam (2003b).

To conclude, Hemmer and Lorenz (2004, p. 198) argue that despite all statistical and conceptual issues, examinations of growth patterns by means of regression analysis (including the study of convergence) can provide useful results by revealing particularly distinctive regularities that remain hidden in single-case studies.

The next section presents a selection of studies on convergence of both per capita income and other economic variables that proved influential for the analysis of material productivity convergence in this dissertation.

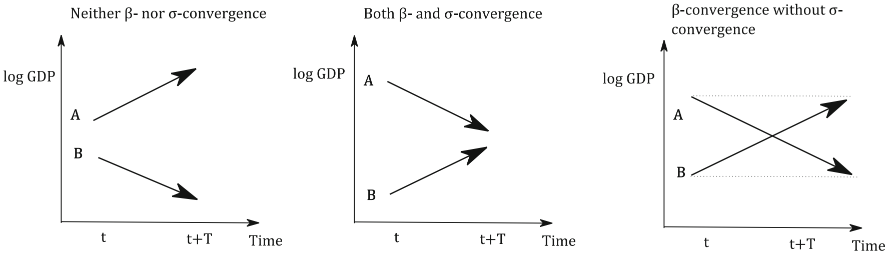

Fig. 4.6 The relation between σ- and β-convergence. *Source*: Sala-i-Martin (1996, p. 1021)

4.3 Some Empirics of Convergence

Cross-country convergence of per capita income and other economic variables has been examined in a large number of studies within the last 25–30 years. A summary of the most influential contributions can be found for instance in Durlauf et al. (2005), Hemmer and Lorenz (2004), and Islam (2003b). In this chapter only the studies that influenced the following analysis of material productivity convergence will briefly be mentioned and their main findings with regard to convergence will be presented.

"Growth-initial level regressions" as Islam (2003b) describes it formed the initial stage of convergence studies. Baumol (1986) and Abramovitz (1986) are the most prominent examples of this type of study. Baumol (1986) analyzed a sample of 16 OECD countries between 1870 and 1979 and found a significantly negative estimate for the coefficient on initial income which he interpreted as strong evidence for unconditional β-convergence within the OECD sample. When he considered a larger sample of 72 countries between 1950 and 1980, no negatively sloping pattern could be identified, and the regression even yielded a slightly positive slope, indicating divergence rather than convergence. In a second step he then divided the sample into the 16 OECD countries from the previous examination and centrally planned economies as well as other economies. Here, Baumol identified a pattern of club-convergence for the OECD and the centrally planned economies, with each constituting its own club.

Abramovitz (1986, p. 386) also examined the hypothesis that "in comparison among countries the growth rates of productivity in any long period tend to be inversely related to the initial levels of productivity." He proposed that the larger the technological gap between a "leader" country and a "follower" country, the stronger the potential of the follower to realize productivity growth, thus "catching-up" to the leader through the replacement of its obsolete capital stock (other things being equal). In his empirical analysis, he used the data for the same 16 OECD countries as Baumol (1986) but rather than conducting a regression he measured the catch-up process by comparing the levels of labor productivity of the 15 countries relative to the USA. Moreover, he calculated a rank correlation between the initial levels and the subsequent growth rates of labor productivity. He found a declining of the variance measures (mean relative to the USA and coefficient of variation) as well as an increase in the correlation coefficients. He concludes that they "should be interpreted to mean that initial productivity gaps did indeed constitute a potentiality for fast growth that had its effect later if not sooner" (Abramovitz 1986, p. 394).

Barro (1991) identifies absence of unconditional or absolute convergence in a broad sample of 98 countries. However, when human capital is included in the analysis it can be shown that subsequent growth is related positively to measures of human capital and negatively to the initial level of per capita GDP. He concludes that in a "modified sense, the data support the convergence hypothesis of the neoclassical growth models" (Barro 1991, p. 409). He also examined the influence of a range of other explanatory variables such as fertility, investment, political stability, etc., on economic growth. This study is also often seen as the starting point for the so-called Barro regressions studying alternative growth determinants besides those suggested by the Solow model (Durlauf et al. 2005). Islam (2003b, p. 318) argues that Barro's convergence in a modified sense "can be viewed as the germination of the concept of 'conditional convergence.'" Soon after the study by Barro, convergence analysis entered into its "formal specification" stage (Islam 2003b, p. 319).

The development from the previous informal, inchoate, and not model-based stage to a formal, model-based specification of the concept of conditional convergence was accomplished by Barro and Sala-i-Martin (1992) and Mankiw et al. (1992). They both derive the regression specifications for convergence formally from the neoclassical growth model (an abbreviated description of the procedure can be found in Sect. 4.1.1.2). The speed of convergence, i.e., the rate with which the gap between the steady-state income and its current value is closed, can then be estimated and it is determined by the values for the capital share coefficient, population growth, the rate of technological progress, and the rate of depreciation. In their empirical application, Barro and Sala-i-Martin (1992) identify unconditional convergence for the US states over different periods between 1840 and 1988. For a sample of 98 countries worldwide between 1960 and 1985, they found conditional convergence. Mankiw et al. (1992) examined 98 non-oil countries between 1960 and 1985 for convergence. These were divided into two groups OECD and intermediate. They found conditional convergence for the different groups.

There are various other studies examining convergence in a cross-section context, which will not be discussed further here. An overview can be found for instance in Islam (2003b) and Durlauf et al. (2005). Generally, amongst the cross-section studies an agreement to the broad result of conditional convergence appears to be present (Islam 2003b, p. 324).

The limitations of the cross-section approach to convergence analysis led to the development of a panel-based approach (Islam 2003b). The analysis of Islam (1995) is a prominent example of this approach to convergence analysis. He identifies conditional convergence, though with a higher convergence rate than in the cross-sectional application in the same sample as in Mankiw et al. (1992) dropping two countries.

Besides conditional convergence the term club convergence also appears in the literature. It originates in Baumol (1986) who identified 16 developed countries and the centrally planned economies as two separate clubs. A formalization of this idea can be found in Durlauf and Johnson (1995) and Galor (1996). The theoretical distinction between conditional convergence and club convergence is centered around the uniqueness of the equilibrium. In the case of conditional convergence a single, unique equilibrium is assumed. This may however differ between economies so that each economy approaches its own equilibrium. In the case of club convergence, the existence of multiple equilibria is assumed. Which equilibrium an economy will reach depends on either its initial position or some other attribute. A group of countries will approach the same equilibrium if they share the same initial location or other attribute determining the equilibrium, thus displaying club convergence (Islam 2003b, p. 315). Empirically, however, it is difficult to distinguish club convergence from conditional convergence. Despite theoretical and empirical difficulties, Islam (2003b) argues that stylized facts on cross-country growth regularities ("twin peaks") indicate that further research on club convergence may be worthwhile. It has been argued by Aghion and Howitt (2009, p. 151) that most empirical evidence seems to point towards "club-convergence" since the mid-twentieth century and that "most rich and middle-income countries belong to the convergence club," a club with a common long-run growth rate. Many poor countries, however, have been excluded from this club and have strictly lower long-run growth rates.

Developing in parallel to the panel-based approaches, time-series-based concepts of convergence emerged, starting with Bernard and Durlauf (1995) and Evans and Karras (1996). Bernard and Durlauf (1996) examined per capita income for 15 OECD countries from 1900 to 1987. They found no convergence according to the strict sense of the definition of time-series convergence. However, due to cointegration between the countries they concluded that a set of common factors existed which influenced long-run growth in their sample. Evans and Karras (1996) used a panel unit-root test to examine convergence. They also tested for convergence according to the weak sense definition both for the 48 US states between 1929 and 1991 and for a sample of 54 countries worldwide in 1950–1990 and found convergence to be present in this sample. A variety of other studies applied time-series methods in order to analyze convergence in different contexts, for instance, Pedroni and Yao (2006), Pascual and Westermann (2002), or Scarpetta and Tressel (2002). Generally, time-series analysis also seems to support a variant of conditional convergence (Islam 2003b, p. 336). Further developments of the approaches suggested by Bernard and Durlauf (1995) and Evans and Karras (1996) can be for instance be found in Pesaran (2007) or Breitung and Pesaran (2008). They have not however been subject to further research in the context of this dissertation.

With regard to σ-convergence, there seems to be little disagreement in the literature. The evidence depends extensively on the sample (Islam 2003b, pp. 338–340). For the OECD countries there appears to be a tendency towards σ-convergence. For larger, global samples of countries the evidence does not indicate σ-convergence but rather a rising of the variance of per capita incomes (see for instance Lee et al. 1997).

A general overview of the broad agreements regarding the presence or absence of convergence of per capita incomes can be found in Islam (2003b, p. 314). He concludes that despite different approaches, the evidence for conditional β-convergence is relatively robust, both for developing and developed economies. In the developed economies evidence for unconditional β-convergence can sometimes be found. The analysis of σ-convergence generally focuses on unconditional convergence. Therefore the results with regard to σ-convergence correspond to the results regarding unconditional β-convergence. Evidence for σ-convergence can be found in the samples of developed economies which have been found to display unconditional β-convergence. Again, in line with unconditional β-convergence analysis no σ-convergence can be found in large global samples. Time-series analysis of convergence has also yielded results corresponding to a notion of conditional convergence.

Besides income convergence, convergence of other economic variables such as total factor productivity and its individual components like labor productivity or energy productivity, CO_2 emissions and environmental variables, human development, or life expectancy were examined for convergence. A few of these convergence studies will be discussed next in order to show how the concept of income convergence has been transferred to other variables previously.

The question whether a technological catch-up takes place, which can in turn contribute to income convergence, is addressed by studies examining total factor productivity (TFP) convergence. Researchers have investigated whether the TFP levels of countries have approached each other over time using the closest measure to technology available, namely, total factor productivity. Income convergence is related to TFP convergence in the sense that it can accelerate if initial differences in TFP narrow over time and vice versa (Islam 2003b).

Dowrick and Nguyen (1989, p. 1010) doubt the apparent convergence of labor productivity and per capita income and explain that "it remains to be demonstrated whether or not poorer countries grew faster simply because they experienced faster rates of capital deepening and/or more rapid rises in labor participation." They suggest that there exists a distinction between convergence of per capita income or labor productivity and a tendency for catching-up in levels of TFP. In addition, TFP catch-up implies a tendency for income convergence; however, this tendency may be masked or exaggerated depending on the growth of the factor intensities. In their analysis of income and TFP convergence amongst OECD countries between 1950 and 1985 Dowrick and Nguyen identify TFP catch-up as a dominant and stable trend. They consider TFP catching-up as an important phenomenon to be considered when attempting to explain differences between growth rates of OECD member countries. Similarly, Wolff (1991) finds convergence of TFP levels in the G7 in the period 1870–1979. He also argues that income convergence may be the result of a technological catching-up process of countries lagging behind in terms of technology. If the technology in these countries displays large growth rates due to catching-up, this would imply convergence of TFP levels. Dollar and Wolff

(1994) find evidence of TFP σ-convergence in aggregate TFP in 14 industrialized countries as well as within industries between 1963 and 1985. A series of other contributions to the examination of convergence of total factor productivity both economy-wide as well as on a sectoral level exist, for instance, Bernard and Jones (1996a, b), Miller and Upadhyay (2002), Pascual and Westermann (2002), Scarpetta and Tressel (2002), and Islam (2003a).

Mayer-Foulkes (2001) addresses the issue of convergence clubs using cross-country patterns in life expectancy during the period 1962–1997. He shows that "life expectancy dynamics can be modelled using theories of economic growth and that they must reflect the convergence club structure of any underlying theory" (p. 2). Given that life expectancy and income is closely linked and that health is associated with income and growth he argues that life expectancy can be modeled in terms of theories of economic growth. From his model it follows that when an economy converges to a steady state, life expectancy will also converge to a corresponding trajectory. In the case of several steady states, several life expectancy trajectories will exist. His empirical analysis of countries' life expectancy suggests at least three large-scale convergence clubs. These consist of one club of countries with low levels in life expectancy in 1962 and stagnation, a second club with initially low but rising life expectancy, and a third club with relatively high levels of life expectancy in 1962.

In his 2010 paper Mayer-Foulkes conducts a cross-country analysis of the components of the Human Development Index (HDI) income, life expectancy, literacy, and gross enrolment ratios. He uses a descriptive analysis to reveal complex patterns of convergence and divergence. He argues that development is not smooth but consists of transitions from increasing divergence to convergence. Each of the components of the HDI follows its own set of transitions and they are interlinked differently at different stages of development (Mayer-Foulkes 2010).

Miketa and Mulder (2005) examined convergence of energy productivity in ten sectors of the manufacturing industry in 56 countries, both OECD and non-OECD, for the years 1971–1995. In all but one sector they found a reduction of the dispersion of absolute energy productivity levels and thus σ-convergence. The examination of β-convergence by panel methods indicates the catching-up of less advanced countries to a local steady state and thus conditional β-convergence.

Mulder and Groot (2007) as well as Miketa and Mulder (2005) analyzed the development of international differences of energy productivity and labor productivity amongst 14 OECD countries for 1970–1997 on a sectoral level. Regarding σ-convergence the level of aggregation seems to be important. On a macroeconomic level (comprising of the sum of the sectors manufacturing, transport, services, and agriculture) they found divergence of energy productivity and convergence of labor productivity. Generally, cross-country variation of energy productivity seems to be more pronounced than cross-country variation of labor productivity. Even though some degree of convergence can be found, cross-country differences in labor and energy productivity are persistent. Moreover, they use panel methods to identify the presence of conditional β-convergence for both labor and energy productivity. However, energy productivity displays a faster rate of convergence.

Le Pen and Sévi (2010) examined stochastic or time-series forecast convergence of energy intensities for a group of 97 countries between 1971 and 2003 by means of the method proposed by Pesaran (2007). They found no evidence for global convergence of energy intensity. However, patterns of convergence could be found in the samples of the Middle East and the OECD countries. In addition, LePen and Sevi provide a good overview of recent studies on energy productivity, energy intensity and carbon dioxide emissions convergence.

Barassi et al. (2011) also provide an overview of recent studies on CO_2 emission convergence and themselves show that CO_2 emissions within the OECD between 1870 and 2004 converged over time, though slowly.

Panopoulou and Pantelidis (2009) examined 128 countries for the period 1960–2003 for σ-convergence. They used a clustering algorithm to classify countries into clubs. Their results suggest the existence of two convergence clubs converging to different steady states. They also found evidence of transition between clubs. This may be explained either by slow convergence between the two clubs or by a tendency of some countries to move from one club to another. They also examined convergence within subgroups with similar economic characteristics. Convergence seems to take place for high- and middle-income countries while low-income countries diverge. They also conclude that CO_2 emission convergence occurs in parallel with income convergence.

Chapter 5
Material Productivity Measurement

In order to measure material productivity, information on material use is combined with economic indicators like GDP. Material flow analysis is used to obtain information on material use and material flows in an economy. This method is presented and discussed in the Sect. 5.1. Basic theory on productivity indicators is presented in Sect. 5.2 and their benefits and shortcomings are discussed.

5.1 Material Flow Analysis

Material flow analysis (MFA) is a tool used to measure the socioeconomic metabolism of societies, thus providing information on the material and energy which enters a society or economy in the form of inputs and leaves again as outputs (Eurostat 2001a). This chapter presents the basic concept and intellectual origins of material flow analysis and MFA tools. In addition to the uses of material flow analysis, the most commonly used indicators are discussed, and its main limitations are explained.

5.1.1 Intellectual Origins of Material Flow Analysis

Intellectually, the idea of a societal metabolism has its origins in the late 1960s, although its history goes back to the 1860s. When the negative effects of economic growth and environmental considerations became more prominent in the 1960s, the concept of a society's metabolism found its way into the social sciences. Fischer-Kowalski (1998) and Fischer-Kowalski and Hüttler (1998) provide a literature overview on intellectual background of the conceptual origins of material flow analysis. They argue that in the 1960s it became increasingly accepted that physical processes mattered for the organization and development of society. The worries about a "cowboy economy" on "Spaceship Earth" (Boulding 1966) contributed to

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the relevance of this idea. In 1969, Ayres and Kneese published their seminal article arguing that environmental pollution and its control should be viewed as a material balance problem for the economy. Fischer-Kowalski (1998, p. 71) argues that they "basically presented the full program of what in the 1990s was carried out as material flow analyses of national economies."[1] Since the 1970s a variety of studies on the metabolism of industrial societies were conducted. An overview on analyses undertaken between 1970 and 1998 can be found in Fischer-Kowalski and Hüttler (1998).

5.1.2 The Basic Concept of Material Flow Analysis

Generally, the socioeconomic metabolism integrates connections between society, the economy, and the environment, thus forming the three core elements of sustainable development. It promotes a view where the socioeconomic system is embedded in the environment and there is a physical exchange of material and energy (Eurostat 2001a; Bringezu et al. 2009b). In Fig. 5.1 this idea is shown graphically. Both used and unused flows are included in the material balance scheme. Materials and energy are thus withdrawn from the environment to serve as inputs for production and consumption in the socioeconomic system and are finally returned in a transformed state as outputs back to the environment.

The reasoning behind this is the first law of thermodynamics: conservation of matter, which states that material and energy can be neither created nor destroyed by any physical transformation such as a production or consumption process. This means that in a closed system, which the earth can be considered as, at some point in time all inputs will become outputs to the environment again (Eurostat 2001a; OECD 2008b, c).[2]

Material flow analysis monitors and analyzes physical flows of materials into, through, and out of a given system. The focus of the analysis is the relationships between material flows and environmental changes. Depending on the particular focus, the scale as well as the instruments may differ. Material flows can be examined globally, within a national or regional economy, within a city or an ecosystem, but also within an economic activity or an individual firm. The examination of material flows can range from the inclusion of all resources and products flowing through a system to only a group of materials; it can focus on particular materials or single chemical elements (OECD 2008c).

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[1] Others like Neumayer (2010, p. 175) consider F. Schmidt-Bleek with his MIPS concept (material input per service unit) as the first developer of a material flow analysis. For the MIPS concept, see, for instance, Schmidt-Bleek and Klüting (1994) and Schmidt-Bleek and Bierter (1998).

[2] The idea that thermodynamics, a physical concept, can be applied to the economic sphere is attributed to Georgescu-Roegen. An overview on Georgescu-Roegen's arguments regarding thermodynamics and the economy is found in Kraus (1999). Reich (2010) discusses the idea of entropy in the economy critically.

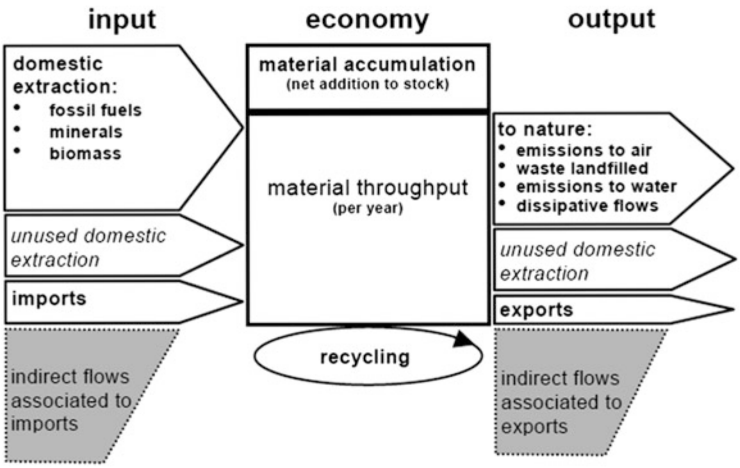

Fig. 5.1 Economy-wide material balance scheme (excluding air and water flows). *Source*: Eurostat (2001a, p. 16)

Conceptually, as already mentioned, MFA is closely linked to the idea of a socioeconomic metabolism and draws on the law of the conservation of matter to arrive at the following accounting identity.

$$\begin{aligned}\text{Natural Resource Extraction} + \text{Import} = {} & \text{Residual Output} + \text{Exports} \\ & + \text{Net Addition to Man-made Stocks}\end{aligned}$$

Thus, material inputs equal material outputs in addition to the changes in stocks. MFA assumes that every movement or transfer of material or energy has an effect on the environment; therefore, the so-called unused and indirect flows are of great importance in the concept. These flows are of no economic use and therefore have no price; however, environmentally they are relevant as they contribute to pollution or alter landscapes. Examples are mining overburden or wastes occurring outside the system under review. These flows are never shown in economic accounts or trade and production statistics and are therefore called "hidden flows" (OECD 2008c).

The OECD (2008c) lists the different tools of MFA which can be classified into six types of analysis. Substance flow analysis, material system analysis, and life cycle assessment are associated with certain substances, materials, and manufactured goods and are concerned with their environmental impact, supply security, and technology development. In contrast, business level MFA, input-output analysis (IOA), and economy-wide material flow analysis consider the environmental and economic concerns of material flows at the level of specific businesses, economic activity sectors, countries, or world regions. Economy-wide material flows are focused upon in this dissertation and will therefore be described in more detail. MFA on a macroeconomic level "provides a comprehensive and systematic overview of the physical resource basis and requirements of all economic activities taking place within a national economy" (ibid, p. 50). Total amounts of materials, groups of materials, or individual materials are monitored. And usually, both the flows entering and leaving the economy (direct flows) and those flows which do not enter the economic process but are associated with upstream resource exploitation as well as materials processing and use (indirect and unused flows) are considered. These flows can help determine environmental pressures, which is the first area in which material flow analysis can prove useful.

5.1.3 The Uses of Material Flow Analysis

Input and output flows (and the accumulation of the stock of materials) can be used to determine the quantity and severity of environmental pressures. Traditionally, environmental policy has focused on the output side of the system, i.e., waste, emission, and wastewater, aiming to minimize their environmental impacts. Outputs to the system are however determined by the inputs coming into the system. This is the point where the concept of socioeconomic metabolism comes into play: it enables a broader, system-wide perspective and can help identify changes between material flows and arising environmental pressures (Bringezu et al. 2009b). In the context of sustainability, it can help to identify problems of unsustainable material flows regarding either quality or quantity of the materials. On the basis of this information, strategies can be developed to tackle those problems, e.g., by means of detoxification or dematerialization (ibid).

The decoupling of economic growth from environmental pressures and dematerialization—the explicit aim of environmental policies—are two closely related concepts (Ekins 2009). Decoupling refers to a decline of the ratio between the amount used of a resource (or of its environmental impact) to the value generated. One can distinguish between relative and absolute decoupling. Relative decoupling indicates improvements in productivity; however, resource inputs (or pollution outputs) continue to increase but at a slower pace than economic output. Absolute decoupling occurs when there is an overall reduction in material inputs (or pollution outputs) while the economy is growing. Dematerialization is characterized by a decrease in the quantity of resources (in mass terms) used in an economy. In a growing economy, absolute decoupling implies dematerialization. In contrast to decoupling, the concept of dematerialization has not received much political attention.

Besides its contribution to measuring decoupling (and dematerialization), MFA is also useful for other areas of concern [see OECD (2008c)]. For instance, sustainable resource management policies require a large amount of information regarding the magnitude and flows of natural resources. However, a knowledge gap exists regarding many aspects of resource use, its connections to ecosystems, and the long-term environmental, economic, and social implications of materials use and resource degradation. Overall, there is insufficient information on how different resources and materials flow through the economy. Material flow analysis can help overcome information deficits and enable informed decision-making. More specifically, it can be useful for economic, trade, and technology development policies, natural resource management policies, and environmental policies. Examples include the measurement of the physical performance of the economy, especially if used in connection with other productivity measures; the monitoring of decoupling of environmental pressures and economic growth; the deriving of indicators for resource productivity and eco-efficiency; the monitoring of the environmental implications of changes in the international material flows; improved understanding of the implications of new technologies; enrichment of conventional natural resource and energy accounts; and enrichment of conventional media-based environmental information systems. This would allow the development of a better understanding of the flow of nutrients, contaminants, or toxics or to estimate the environmental pressure arising from the extraction and production of metals or to identify waste of materials.[3] In order to convey information regarding these issues, indicators are constructed from the material flow accounts.

5.1.4 Indicators of Material Flow Analysis

From material flow analysis, a variety of material flow indicators can be derived, which can help overcome the aforementioned information deficits. The OECD (2008c, p. 16) defines material flow indicators as "quantitative measures, which point to, inform about, describe the characteristics of material flows and material resource use and which have meaning or a significance that goes beyond that directly associated with the underlying statistic."

The following section describes the material flow indicators most relevant in the context of this dissertation. MF indicators in general can serve to describe the use of material resources as well as to inform about the economic efficiency and environmental effectiveness with which these materials are used in the economy, from their production to their consumption and their subsequent disposal (OECD 2008c).

Five main groups of indicators can be distinguished: input indicators, consumption indicators, balance indicators, output indicators, and efficiency indicators. Next, input, consumption, and efficiency indicators are described in detail, as they are relevant for the empirical analysis in later chapters. More details on the full range of indicators can be found, for instance, in OECD (2008c) and Eurostat (2001a).

Material flow input indicators are concerned with the materials mobilized or used to conduct economic activities, which includes the production of export goods and services. Most commonly used are *domestic extraction used* (DEU), *direct*

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[3] For more uses of MFA, see Eurostat (2001a, p. 10).

Table 5.1 Material flow input indicators

Domestic extraction used (DEU)	"DEU measures the flows of materials that originate from the environment and that physically enter the economic system for further processing of direct consumption (they are "used" by the economy). They are converted into or incorporated in products in one way or the other, and are usually of economic value" (OECD 2008c, p. 76).
Direct material input (DMI)	"DMI measures the direct input of material for use in the economy, i.e., all materials which are of economic value and are used in production and consumption activities (including the production of export goods and services); **DMI equals domestic extraction used plus imports**" (OECD 2008c, p. 76, emphasis added).
Total material requirement (TMR)	"TMR includes, in addition to the DMI, the unused flows associated with the extraction of materials that do not enter the economy as products and the (indirect) material flows that are associated to imports but that take place in other countries. It measures the total 'material base' of an economy" (OECD 2008c, p. 76).

Source: Based on OECD (2008c)

material input (DMI), as well as *total material requirement* (TMR). Their definitions can be found in Table 5.1.

Material input indicators are strongly influenced by the mode of production of a country. In addition, changes in patterns of foreign trade, natural resource endowment, or the level of technology and its uptake will strongly affect the indicator (ibid).

Material inputs are classified into three broad categories: fossil fuels, minerals (including metal ores, industrial minerals, and construction minerals), as well as biomass. Imports are classified into six categories: raw materials, semimanufactured products, finished products, other products, packaging material imported with products, as well as waste imported for final treatment and disposal (Eurostat 2001a).

Consumption indicators are structured similarly to input indicators and show how much material is used in the course of economic activity. *Domestic material consumption* (DMC) and *total material consumption* (TMC) are most commonly used. Table 5.2 shows definitions and calculation rules. Consumption indicators are closely related to the consumption patterns of an economy and are more stable over time than the input indicators (ibid, p. 77).

A wide range of data sources exists for the calculation of material flow (MF) indicators. For the calculation of input indicators, the main sources for material inputs include forestry statistics and accounts, agricultural statistics, industry and production statistics (for instance, extraction of fossil fuels and crude ores), energy statistics and energy balances, input-output tables, as well as estimates. Data on material imports is drawn from foreign trade statistics [for more details on data sources, see Eurostat (2001a)]. The classification of imports is undertaken according to their level of manufacturing into raw materials, semimanufactured products, finished products, and other. It is clear for base materials like coke (semimanufactured fossil fuel), pig iron (semimanufactured metals), or copper

Table 5.2 Material flow consumption indicators

Domestic material consumption (DMC)	"DMC measures the total amount of material directly used in an economy (i.e., excluding indirect flows). DMC is defined in the same was as other key physical indicators such as gross inland energy consumption. **DMC equals DMI minus exports**" (OECD 2008c, p. 77, emphasis added).
Total material consumption (TMC)	"TMC measures the total material use associated with domestic production and consumption activities, including indirect flows imported (see TMR) less exports and associated indirect flows of exports. **TMC equals TMR minus exports and their indirect flows**" (OECD 2008c, p. 77, emphasis added).

Source: Based on OECD (2008c)

ware (finished metal product). For other products, it is more complex. Eurostat (2001a) provides conversion tables which take into account the share of "dominant" as well as "secondary" materials.

Efficiency indicators combine economic output indicators like GDP or value added with economy-wide or sectoral MF indicators. They can therefore measure the material productivity or material intensity of an economy (OECD 2008c). Material productivity refers to the output indicator divided by the material flow indicator whereas material intensity relates the material flow indicator in the numerator to the economic output indicator in the denominator. For example, domestic material productivity—defined as GDP per DMC (GDP/DMC)—can be used to identify the amount of material consumed to create one unit of GDP. Material productivity can be calculated in different ways, either with regard to economic-physical efficiency, i.e., monetary value added per mass unit of inputs, or with regard to physical or technical efficiency, i.e., the amount of materials necessary to produce one unit of output, or as in this dissertation, regarding the economic efficiency, i.e., the monetary value of outputs relative to the monetary value of inputs. Indicators of material productivity can be put to several uses, such as for monitoring the decoupling of material use from economic growth, for comparing levels of material use and productivity across countries, and for identifying material-intensive sectors. Material productivity indicators are useful for identifying key trends and highlighting opportunities and problems; however, for some applications like productivity analysis or the examination of reasons for differences between countries, a more detailed view can be advantageous. Uses include, for example, the breakdown of the data on sectoral activity or individual material/ mineral categories or the examination of the underlying values in denominator and nominator separately. Lastly, material productivity measures help by complementing existing productivity measures like labor and capital productivity in order to provide more information on total factor productivity and its development (OECD 2008c).

5.1.5 Limitations of Material Flow Analysis

Limitations of MF indicators arise from several inherent characteristics [see OECD (2008c), and Neumayer (2010)]). First of all, the aggregation of different material flows has methodological and communicative advantages; however, this also leads to some limitations regarding informational content and applicability. A high aggregation of materials can mask variations in the quantities of the materials or the monetary values and the domination of one material may hide the development patterns of other materials. Cleveland and Ruth (1999) similarly argue that material quality is ignored, i.e., the marginal amount of economic output generated per mass unit of material input. There are data availability problems, especially regarding unused and indirect flows, which may have an influence on the information an indicator can provide.

Additionally, the use of aggregated input or consumption indicators in order to draw conclusions regarding the environmental impact of material use poses a problem. The environmental impact of a material does not depend on its weight but rather upon its chemical and physical properties, as well as management of the material. Weight, however, is the scale used by MF indicators. Gawel (1998) argues along the same lines. He claims that one cannot add up two different forms of material throughput with different environmental damage potential and receive a meaningful result. Smaller volumes of materials may not be less harmful for the environment, depending on their characteristics. He argues that comparisons of per capita material use are meaningless. The problem of differing environmental impacts depending on chemical and physical properties can be at least partially remedied by the use of information from sub-accounts and material flow analysis differentiated according to the materials' properties. This was accomplished, for instance, in the Environmentally weighted material consumption (EMC) in van der Voet et al. (2005) and Best et al. (2008). When it comes to describing environmental pressures, MF indicators can be used as proxies for potential environmental impacts; however, they cannot be used to "establish a direct cause-relationship between resource exploitation and use, actual environmental impacts and subsequent changes in environmental conditions" (OECD 2008c, p. 81). On the other hand, it has been shown by van der Voet et al. (2005) that the DMC is correlated with the EMC, which is able to measure environmental pressures more accurately and that the TMR indicator is correlated with the DMI indicator.

These findings support the assumption that a reduction in material use will lead to a reduction in environmental pressures and, consequently, the idea that material efficiency needs to be increased to relieve the environment. In the light of these insights Bringezu et al. (2009b) pose the question of whether more easily available indicators might be used as proxy indicators of environmental impacts. They debate whether DMC values in 1-year intervals could serve as basis for policy guidance. They conclude that focusing only on DMC or DMI may be misleading. Instead the authors argue that flanking them with more "complete" indicators such as TMR or

EMC possibly in larger time intervals of 3–5 years in order to ensure that transnational resource use and related pressures are considered may be advisable.

Another concern is that direct input and consumption indicators are not able to offer a full picture of environmental pressure, as they do not consider hidden flows. Therefore, the ability of the indicator DMC to measure decoupling may also be limited, as DMC considers only direct and not indirect flows. The aim of decoupling is to de-link output and material consumption as well as environmental pressures. However, de-linking only domestic material consumption from output while excluding material use occurring in other countries during the extraction or production of materials will not contribute to the overall reduction of material use in the context of sustainability. Indicators like TMR or TMC are able to take indirect flows such as unused extraction into account and are thus able to provide a fuller picture of material use. However, they are more difficult to construct.

Dittrich et al. (2011) highlight the role international trade plays for the indicators of material productivity. Countries that display high material productivities when indirect flows are excluded may be considerably less material efficient if indirect flows are taken into consideration. For example, the Republic of Korea, a country with a comparably high level of material productivity, has outsourced resource-intensive industries to other countries. Instead of extracting and processing materials domestically, raw materials and semifinished products are imported. Thus, the productivity of materials used in the economy is high. If indirect flows are considered, the total material use including indirect flows at the origin of the materials is taken into account and the material productivity is considerably lower. The authors argue that in order to ensure that international trade and outsourcing of production does not bias the material productivity of different countries, comprehensive material flow analysis indicators like TMR or TMC are necessary.

Analytical issues include problems arising as DMI and DMC include material inputs in the form of raw materials as well as in the form of products, which may lead to a lack of internal coherence. External coherence with national accounts can become problematic and can only occasionally be corrected for. Besides, most indicators are not internationally additive, i.e., to avoid double counting, regional totals have to be calculated. Lastly, problems arise due to the measurement of variables such as domestic unused extraction or emissions to water, consequently leading to problems with the accuracy of the indicator.

Despite the limitations of material flow indicators, they are a useful tool for raising awareness and monitoring progress; moreover, they are easy to understand and theoretically sound [for more details, see OECD (2008a, pp. 79–85)].

5.2 Productivity Indicators

“Productivity” is a word used extensively and loosely (Morrison Paul 1999, p. 24). This chapter will present the definition and theoretical basis of productivity and productivity indicators, their purposes, as well as their issues and limitations.

Productivity describes the relationship between an output and the inputs required to generate it. This leads Schreyer and Pilat (2001) to conclude that “in principle, productivity is a rather straightforward indicator” (ibid, p. 128). The OECD (2001b) specifies that productivity is usually “defined as a ratio of a volume measure of output to a volume measure of input” (ibid, p. 12). Conceptually, the basic idea is that technical change results in a shift of the production function, changing the input–output ratio. This shift either increases the output–cost ratio (output per dollar) or decreases the cost–output ratio (input cost per unit of output). Thus, the basic idea is that productivity works in helping produce more goods, i.e., greater real output, with given resources or inputs or in producing a given output with fewer resources or inputs. With increased efficiency of production, more goods can be produced from scarce resources (Morrison Paul 1999).

This idea, straightforward as is seems, raises several issues when it comes to measuring productivity, because changes in productivity can be the result of many different determinants for changes in output and inputs (Morrison Paul 1999). Before the measurement of productivity is discussed in more detail, the different uses of productivity analysis will be presented briefly (see OECD 2001b).

5.2.1 Uses of Productivity Analysis

Wiegmann (2008) sums up that the most important objectives of productivity analysis are the tracing of technology, identifying changes in efficiency, and describing real cost savings. In addition, productivity can be used to benchmark production processes and to assess living standards.

Perhaps most frequently, productivity growth is used to measure technical change. It examines the development of efficiency dynamically between two points of time. In this context, it is especially important to separate the effects of technical progress from the effects of improvements in the efficiency in the productivity measure. Technical progress shifts the production possibility frontier outwards (or an inward shift of the isoquants in a micro framework), whereas efficiency improvements represent a movement towards the frontier. Both of them result in an increase in the productivity measure, but the reason for the increase cannot be explained by the productivity measure (Wiegmann 2008).

The concept differs slightly when it is used to identify changes in efficiency. Technical efficiency refers to a production process in which none of the factor inputs can be reduced without also reducing the output, or put differently, the maximum amount of output physically achievable with current technology is produced with given inputs. If inefficiencies are present the production frontier is not reached and instead production takes place below the frontier. An increase of the efficiency with a given state of technology consequently increases output. This movement towards the frontier is reflected in a change of the output–input ratio, which can be measured using productivity measurement. This means that the focus lies on the elimination of technical and organizational inefficiencies in order to move towards a "best practice" (Coelli et al. 2005; Wiegmann 2008; OECD 2001b). The OECD (2001b) points out that not every form of technical efficiency makes economic sense. But the profit-maximizing behavior of firms leads to allocative efficiency. Allocative efficiency refers to "the ability of a firm to use the inputs in optimal proportions, given their respective prices and the production technology" (Coelli et al. 2005, p. 51).

Conceptually, it is very difficult to distinguish between the different types of efficiency change, technical change, and economies of scale, which may allow the output to increase without increasing proportionally all inputs. Given that productivity is measured residually, it may include all kinds of other factors. Thus, it can be argued that behind productivity growth is a variety of sources, which can be understood and labeled as real cost savings. Productivity measurement could then be considered a tool to identify real cost savings in production (OECD 2001b).

In business economics, productivity measures can be used to compare specific production processes in order to identify inefficiencies. These productivity measures are very specific and cannot be aggregated easily but serve their purpose of factory-to-factory comparisons (OECD 2001b).

Finally, productivity is also used to measure living standards. For example, per capita income as a major measure for living standards is closely related to labor productivity (value added per hour worked). As a consequence, the measuring of labor productivity can help to better understand the development of living standards (OECD 2001b). Similarly, the OECD (2008c) recommends using resource or material productivity to measure issues of sustainable development and sustainable resource use.

5.2.2 The Basics of Productivity Measurement

Actually measuring productivity is not as simple as its straightforward definition implies (Morrison Paul 1999). Productivity growth indicators are designed to reflect the output changes from technical progress. They are very common measures for the economic performance of a firm, an industry, or an economy. Productivity indicators are constructed from various components which are sometimes individually used as economic performance indicator such as output growth or employment. When these components' underlying overall productive performances are combined in multifactor productivity measures, some insight into the overall productive performance can be gained. Although many different productivity measures exist, a broad classification can be undertaken according to the type of measure. Namely, these entail multifactor versus single-factor productivity, as well as measures according to their technical construction, i.e., nonparametric versus parametric measures, and relevant at industry or firm level, the distinction between measures based on gross output and those based on the concept of value added (OECD 2001b; Morrison Paul 1999). As this dissertation centers on an international comparison of single-factor productivities compared between economies, the latter two distinctions do not play a major role for the present analysis and will therefore be mentioned only briefly before single and multifactor productivities are discussed in more detail.

Technically, one can distinguish between productivity measures that are calculated parametrically and those which are calculated nonparametrically. For parametric estimation, the factors of the production function are estimated econometrically. This approach does not rely on model assumptions like the relationship between production elasticities and income shares; rather, it allows adjustment costs and variations in factor utilization. It can investigate other forms of technical change besides Hicks-neutral technical change and does not require assumptions to be made about constant returns to scale. For nonparametric estimation, productivity is defined economically by means of theoretical properties of the production function and conclusions from the theory of production. Then empirical measures are chosen which are able to approximate the "true" actually unknown productivity. Growth accounting pioneered by Solow (1957) is a very well-known example for a nonparametric technique (OECD 2001b).

For analysis at an industry or firm level, a distinction must be made between gross and value added output, in order to avoid counting the contribution of the different production stages twice. For instance, when calculating the productivity of the shoe and leather industry, the intermediate flows between the two industries need to be taken into account in order to avoid double counting (OECD 2001b, p. 94).

At the most fundamental level, single-factor productivity (SFP) measures must be distinguished from multifactor productivity measures. Single-factor productivity measures are "the earliest and most easily computable measures of productivity growth" (Morrison Paul 1999, p. 25). Labor productivity, capital productivity, and energy productivity are examples of established single-factor productivity measures. They measure how productively the respective input is used to generate output over time. Changes in SFP reflect not only changes in the productivity of the respective input but also other influences. For instance, changes in labor productivity result from changes in capital and intermediate inputs or changes in technology, organization, or efficiency within or between firms. Economies of scale can play a role as well as differing degrees of capacity utilization and measurement errors. Also, labor productivity can only reflect to a limited extent how capable workers are or how much effort they invest. When measured in a gross output context, single-factor productivity measures also depend on the ratio of intermediate inputs to changes in the input factor under consideration. For instance, in the case of outsourcing, gross output-based labor productivity will rise and fall when in-house production is conducted. This change in productivity obviously does not result from a change in the characteristics of the workforce and it does not necessarily reflect a technology shift or efficiency change. SFP measures can show how efficiently the input under consideration is combined with other production factors, how many of these other production factors are available per unit of input, and how rapidly technical change proceeds. However, the advantage of SFP measures is that they are relatively easy to construct and interpret. In addition, in the case of gross output-based measures, only price indices of gross output are required for their construction (OECD 2001b; Morrison Paul 1999).

The use of SFP measures is usually motivated by a specific application. If wage negotiations are to be held, labor productivity becomes important (Morrison Paul 1999). Similarly, the debate about sustainability or "green growth" forms the motivation for material productivity measurement in most cases.

Analogous to other SFP measures, material productivity measures how material consumption relates to output and can help in the comparison of material requirements between countries. Similarly, to labor productivity, material productivity can only partially reflect the quality or characteristics of the materials, for instance, high-grade ores versus low-grade ores. Material productivity reflects the joint effects of changes in labor and capital inputs as well as changes in overall productivity.

However, by focusing on the productivity of a single input, SFP measures imply that this is the only scarce input. Naturally, this is not true. They ignore substitution of this input as a consequence of a change in the relative prices as well as differences in technical efficiency and input composition at different scales of output production. Morrison Paul (1999, p. 28) warns that "although single-factor measures may sometimes be relevant, application and interpretation of a single factor measure is often questionable." She argues further that increases in labor productivity, land productivity, or material productivity embody different market and technological changes, like changes in the input composition. This is due to changes in relative technical efficiency or in prices and that these changes are simply attributed to the productivity of the single factor under consideration. Even if productivity increases, it is impossible to determine whether productivity as a whole has increased, as only one input, i.e., one component of costs and therefore efficiency, is considered. It also fails to consider the substitution of other scarce resources which could increase productivity. In the case of material productivity, this may occur if a bulk material is replaced by a material with less mass. SFP measures indicate that "no matter how expensive in terms of other inputs" (ibid, p. 29) any increase in the productivity measure is considered an improvement in performance. Obviously, this can only explain economic performance to a very limited extent. Therefore, in the strategies for sustainable development or "green growth," material productivity is only one of several indicators measuring progress.

Multifactor productivity (MFP) measures can be used to overcome these issues. They include changes in the use of other inputs and provide a clearer picture of overall productivity. To sum up, a major limitation of SFP measures is that they are only partial measures of productivity, reflecting the combined effects of many different factors. This factor might be the reason for the common misinterpretation of these measures as technical change or the productivity of, e.g., individuals in the labor force or materials in the production process (OECD 2001b).

However, while individual measures have only limited power in explaining overall productivity, their combination can provide useful results with regard to the different forces that cause growth. In a growth-accounting context, SFP measures are specified for all recognized inputs and are then used to dismantle the changes in output growth according to their sources. Possibly the most fundamental problem of ignoring substitution between the factors can thus be overcome with multifactor productivity measures (Morrison Paul 1999). They can help dismantle overall output growth into the contributions of labor, capital (or other production factors considered), and intermediate inputs as well as technology (OECD 2001b). The basic idea underlying the calculation of multifactor productivity measures is that Hicks-neutral technical progress affects all factors of production equally so that output Y is produced with capital K, labor L, as well as intermediate products M and technical change A according to

$$Y = A\,F(K, L, M). \tag{5.1}$$

Taking logarithms, differentiating with respect to time and rearranging shows that multifactor productivity growth or the change in the variable A can be measured as the residual of the rate of change of the volume output minus the weighted rates of change of inputs

$$\frac{\mathrm{d}\log A}{\mathrm{d}t} = \frac{\mathrm{d}\log Q}{\mathrm{d}t} - s_L \frac{\mathrm{d}\log L}{\mathrm{d}t} - s_K \frac{\mathrm{d}\log K}{\mathrm{d}t} - s_M \frac{\mathrm{d}\log M}{\mathrm{d}t}. \tag{5.2}$$

The weights attached to the inputs correspond to the revenue shares of each factor in total gross output (Schreyer and Pilat 2001).[4]

However, this technical change is not the only factor which can cause MFP to grow as the residual also picks up non-technological factors such as adjustment costs, scale effects, and pure changes in efficiency as well as measurement errors.

5.2.3 Measurement Issues with Productivity Indicators

When productivity is measured three categories of variables are important: the quantities of outputs and inputs, thus output and input measurement, as well as prices. The major challenges with the construction and use of productivity indicators can be seen in connection with these types of variables. Additionally, when GDP is compared internationally, as it is necessary for international comparisons of productivity, the GDP in national currency units needs to be converted into a common currency in order to make comparison possible (Coelli et al. 2005). The most important aspects with regard to these issues will be discussed briefly.

When output is measured, the issues of independence of measures of output from measures of input as well as the issue of quality change are most prominent [see Schreyer and Pilat (2001) and OECD (2001b)]. In order for productivity measures to be valid, output measures have to be independent from input measures. In the

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[4] For detail, see Solow (1957). Growth textbook summaries can be found for instance in Barro and Sala-i-Martin (2004) or Aghion and Howitt (2009).

case of material productivity, output and input measures can be expected to be independent. Estimates of material consumption for biomass such as grazing of animals are independent of output; instead, they are based on agricultural statistics. Volume output measures need to be transformed into quantity output measures so that price increases are netted out from output growth. In order to obtain quantity measures, current-price output series are divided by an appropriate price index; this is called deflation. The construction of appropriate price indices is a complex task which is discussed elsewhere and centers around the choice of index in terms of chain indices or direct comparison [see, for instance, Eurostat (2001b), Eurostat and OECD (2006)]. Deflating gross output, thus dividing an index of nominal value output by an output price index, is fairly straightforward. More complex is the valuation of quality changes of existing goods as well as the question of how new goods are accounted for in price indices. If only output quantities and their prices are considered, this may also bias the productivity measure as the product quality might have changed dramatically. Thus, not only changes in quantity and price but also changes in quality should be accounted for. Hedonic measurement techniques are an example of how this issue is dealt with. If quality changes are not accounted for, it could be the case that the output remains the same. However, it can also be the case that quality improvements have induced an increase in price and the productivity measure therefore shows decreased production efficiency, which has not actually occurred. New goods can be classified depending on whether they are substitutes and can therefore be treated jointly with another item or if they are actually a new type of item within a product class, then a new subcategory should be opened (OECD 2001b).

The second issue relates to the measuring of inputs. In the case of material productivity indicators, the measurement of material inputs or consumption is done via material flow analysis.[5] One major problem with this approach includes the aggregation of very different materials into one aggregate in mass terms (for more details, see Sect. 5.1). As this dissertation only considers single-factor productivities, the prices of inputs are not an issue.

The third important aspect when measuring productivity and comparing it internationally is that the comparability of GDP data, and thus productivity indicators, needs to be ensured. Before GDP data can be compared internationally, a conversion is necessary, transforming national currencies at national price levels into a common currency at a uniform price level. OECD, Eurostat, and the World Bank recommend using purchasing power parities (PPP) for this (Eurostat and OECD 2006; The World Bank International Comparison Program 2011). Comparisons of prices and volumes of GDP are based on the accounting identity: *value* = *price* × *volume*. For price and volume comparisons, GDP needs to be estimated from the expenditure side, adding all the final expenditures of the country's resident institutional sectors during the accounting period. If the prices are not removed from the values of the GDP, the volumes of goods and services purchased in the

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[5] The measurement of labor inputs and capital inputs is discussed in OECD (2001b).

countries cannot be compared. The differences in the prices can be removed and the expenditures on GDP can be compared by either observing the volume or by using relative prices, thus placing the expenditures on the same price level. The latter is less complex as prices are more easily observable. For international comparisons of GDP, it is necessary that not only GDP is defined and measured in the same way but also that the currency unit and the price level at which GDP is valued is the same. In order to fulfill these last two requirements, conversion rates are necessary. These conversion rates need to convert the GDPs into a common currency and equalize the purchasing power of the different currencies. These conversion rates are called purchasing power parities or PPPs. When PPPs are considered over time, a base year is selected and relative GDP volume levels are extrapolated over the years using the relative rates of GDP volume growth observed in the different countries. Thus, a time series of volume indices at a constant, uniform price level is obtained, which replicates the relative movement of GDP volume growth for each year. Put differently and to sum up, PPPs provide a volume measure of GDP suitable for international comparisons, because different price levels and currencies have been taken into account (Eurostat and OECD 2006).

For both multifactor and single-factor productivity indicators, several additional issues arise, most of them concerning model assumptions of growth accounting. Starting with the occurrence of externalities, it is usually assumed that a representative firm or an aggregated production function includes all factors of production and that their input ratio can be chosen freely by the firm. However, when external effects occur, this is not the case, i.e., when there are factors present that influence production but which the firm cannot control like rain or sunshine in agriculture, public infrastructure such as roads, or institutional settings like taxes or subsidies (Erber and Hagemann 2012).

Furthermore, it is usually assumed that factor inputs are used optimally. However, in reality there might be excess inputs, which are useless for the resulting output. Factor allocation may not be as flexible as the models assume. The same is true for substitution between inputs. Models usually assume average substitution possibilities even though substitution may be limited due to limited flexibility in the production process, e.g., capital for production. Similarly, scale effects are usually not incorporated in models even though they can occur in reality (Erber and Hagemann 2012).

Productivity analysis also generally assumes efficient markets and perfect competition. This assumption may be problematic in reality. If prices are not determined under perfect competition, then productivity measurements are distorted corresponding to the respective price distortions. Another problem concerns the choice of the time period considered. Usually only single periods are examined, so that only short-term productivity or efficiency is taken into account. However, an analysis of the entire life cycle of a product can yield very different results both for individual as well as overall efficiency (Erber and Hagemann 2012).

Also, Erber and Hagemann (2012) argue that there may be market failure when it comes to resource efficiency, since only single periods are considered. Usually, only short-run efficiencies between products are compared and long-run advantages in efficiency are ignored. This is closely related to the question of whether the market sets the right signals for sustainable decisions. A problem closely related to this is the choice of the discount rate. The common method of compounded interest overstates present returns in comparison to long-term returns and favors myopic behavior. They also argue that once the time preference rate is agreed upon, it is possible to rationally discuss the advantages and disadvantages of alternative product developments. Finally, nonmarket production is not incorporated and can therefore bias the productivity measurement (Erber and Hagemann 2012).

For single-factor productivity measures, the additional issue arises of defining input and output in the first place (Morrison Paul 1999). For instance, even if a firm produces only one type of product, output consists of “goods” as well as “bads,” for example, pollution. If the output of a firm or an economy is to be measured correctly, these “bad” outputs have to be taken into account as well. However, this proves rather difficult in reality. Similarly, not all inputs purchased by a firm are dedicated to the production of output for sale, for example, measures to reduce pollution in order to comply with regulations or to contribute in another way that is not directly linked to the production of goods and services. Morrison Paul (1999, p. 26) argues that maybe these types of inputs or contributions should be taken into account when considering the productivity of the inputs as they take the form of assets for a society.

Summing up, a change in the productivity of a single factor such as resource or material productivity can reflect several different effects, for example, substitution of one material for another or other factors of production, shifts in the composition of an economy’s industry, as well as changes in the overall productivity (multifactor productivity change). These are difficult to distinguish between and therefore special care is warranted when interpreting single-factor productivity measures (OECD 2011c).

Before material productivity is analyzed for patterns of convergence or divergence, the next chapter presents a selection of existing studies on material productivity development.

Chapter 6

Empirical Evidence on the Development of Material Consumption and Material Productivity

This chapter presents a few selected studies on material use and material intensity or productivity developments. In addition to reporting the major findings of the studies, wherever possible they are also examined with regard to the question of whether some patterns of convergence or divergence of material productivity can be identified.

Krausmann et al. (2009) provide an overview over developments of material use, GDP, and population during the twentieth century which addresses the long-term perspective of material use. For example, global material consumption increased by a factor of 8.4 between 1900 and 2005, GDP by a factor of 22.8, and material consumption per capita by a factor of 2. Over this period the global population quadrupled. Material intensity declined by 30 %, which corresponds to a 30 % increase in material productivity over the period under consideration. The annual improvements are estimated to accrue to around 1 % per year. However, this efficiency increase did not lead to a decrease in material consumption.

In one of the earlier contributions considering material flows in the European Union in more detail, Bringezu et al. (2004) examined dematerialization for the EU-15 countries as well a selection of countries worldwide including the USA, Japan, Australia, and to some extent China for different time spans depending on data availability. In the first step decoupling was examined with regard to DMI. In the second step they tested the hypothesis that dematerialization results during and as a consequence of economic growth. The same analysis was subsequently conducted with TMR. In the analysis of DMI, they grouped countries according to their performance with regard to the decoupling of the DMI/cap to the GDP/cap. In the low-income countries (GDP < 10,000$ in 1990 US dollars and constant prices), they found no decoupling with the exception of the Czech Republic. Within the high-income countries, very different patterns could be distinguished, ranging from coupling of the DMI/cap with the GDP/cap in Norway, Australia, Belgium/Luxembourg, Denmark, Spain, Sweden, and Austria to constant levels of DMI, while GDP increased in the majority of high-income countries. The countries exhibiting relative decoupling differed quite strongly in their levels of DMI, and whilst basically all of them displayed a relative decoupling over time, the levels of

L. Talmon-Gros, *Development Patterns of Material Productivity*, Contributions to Economics, DOI 10.1007/978-3-319-02538-4_6,

the DMI/cap ranged from up to 45 t/cap in Finland to 13–15 t/cap, for example, in the EU-15, Italy, Japan, and the UK. Generally the DMI seems to follow an upward trend, and the authors argue that in many cases the DMI curve "tends to converge towards a constant level" (ibid, p. 106). As to suggesting reasons for the development path (higher or lower level of DMI/cap), they tentatively propose differences in population density, transport infrastructure, private consumption, and whether or not a country is a net exporter of raw materials. Based on the results of the decoupling analysis, several theories exist on the relationship between GDP and DMI, which were tested statistically (quadratic model, cubic model, logarithmic model, linear model). The econometric analysis shows a trend towards relative decoupling between DMI and GDP and suggests a quadratic function for describing the relation, which suggests a relationship as predicted by the environmental Kuznets curve.

The European Environment Agency (2010) dedicated a complete Thematic Assessment to Material Resources and Waste in the course of its publication series *The European Environment – State and Outlook 2010.* In 2007 average resource consumption (DMC) in Europe corresponded to 16.5 t/cap, which is a 5 % increase compared with the year 2000. The differences between the different countries were very pronounced and reached from 5.4 t/cap in Malta to almost 53 t/cap in Ireland. As to reasons for these differences, the EEA suggests differences in climates, population density, existing infrastructure, whether the country exports or imports raw materials, the main source of energy, economic growth rate, as well as the structure of the economy. Between the years 2000 and 2007, only a few member states were able to reduce their absolute material use (DMC), namely, Belgium and Luxembourg, Germany, France, the UK, and the Netherlands. The accession countries (EU-12) all increased their DMC. On a global level, Japan notably decreased its DMC by 14 %. Material productivity also differs up to a factor of 10 between the member countries. The authors argue that material productivity is determined by several factors, including the structure of the economy, the share of the service sector, consumption patterns, the level of construction activities, as well as the main source of energy. The average material productivity (GDP/DMC) in the EU-27 corresponds to USD 1144/tonne DMC in 2007. In comparison to Japan, it amounted to USD 1800/tonne in 2005. The average material productivity of the new accession countries (EU-12) was considerably lower than in the rest of the EU, and between 2000 and 2007 there was no visible improvement. Between 2000 and 2007 the EU-27 increased its material productivity by 9 %; however, the EU-15 realized growth rates almost twice as high as the EU-12.

Visual inspection of the graphics included in this publication suggests that between 2000 and 2007, the difference between the two extreme users of material resources—Ireland and Malta—increased. The same is true if Ireland and Hungary, the country with the second lowest material consumption, are compared. In this case, this could indicate the absence of σ-convergence in terms of DMC. Also, the comparison between the EU-12 countries, which displayed a lesser use of material in 2000 than the EU-15 countries, shows that they increased their material use even beyond the EU-15 average. With regard to productivity, the difference between the most productive country Malta and the least productive country Romania decreased absolutely between 2000 and 2007. However, comparing the second most productive country—the Netherlands—with Romania, an increase of the dispersion, indicating σ-divergence, can be observed. The difference between the EU-15 and the EU-12 seems to have increased over time. This might be an indication of the absence of σ-convergence. The growth rates of the EU-15 were significantly higher than the growth rates of the EU-12 which suggests the absence of β-convergence.

Bringezu et al. (2009b) provide an overview and comparison of material resource use of the European Union and selected countries worldwide. They consider that a stabilization occurring at a high level of resource use is probable. In 2000 average DMI per head amounted to 18 t/cap in the EU-25, while DMC corresponded to around 16 t/cap. At the same time, the US-American DMI was 25 t/cap, the Finnish amounted to 28 t/cap (1999), and the Chinese to 3 t/cap (1999). Bringezu et al. explain that a relative decoupling of material use and GDP can be observed and confirm their results from the 2004 publication. For some countries realizing economic growth, a stabilized material use can be observed. However, this use differs in levels. At a low level, countries like Italy, Japan, and the UK realized economic growth with a relatively stable DMI of 13 t/cap to 20 t/cap. The Netherlands were able to stabilize their DMI at a medium level (around 28 t/cap) while growing, and at the high level of DMI, stability was observed in Ireland with 40 t/cap. Overall, it appears that for rich countries, the DMI seems to encounter a lower threshold at around 15 t/cap and an upper threshold at around 45 t/cap (for no net exporters of raw materials). Also, the levels of material use differ strongly even between countries with similar incomes. The factors influencing these differences are examined most extensively in the study by van der Voet et al. (2005). In a similar context, Bringezu et al. show that in Germany the manufacturing and construction sectors together contribute to almost 60 % of TMR.

Steger and Bleischwitz (2009) examine the decoupling of GDP from resource use as well as resource productivity and competitiveness for the European Union and the USA. They also found that resource use was higher in the EU-15 than in the new member states and confirm a high variation of DMI per capita levels. With regard to resource productivity (GDP/DMC), generally the EU-15 display a higher resource productivity than the EU-12. Almost all EU-15 countries and the USA were able to increase their resource productivity between 1980 and 2004, except for Portugal and Greece. The same is true when the EU-27, Turkey, and the USA are inspected visually. Only the Slovak Republic, Lithuania, and Greece were unable to improve their performance between 1992 and 2000. Steger and Bleischwitz grouped the countries according to their performance in terms of resource productivity. The UK, Italy, France, and the Netherlands showed a “very good performance”; Austria, Belgium, Germany, and Spain were allocated to the “good performance” part. “Fair performance” was assigned to Ireland, Sweden, Denmark, Portugal, and the USA, while Finland, Greece, and the new member states showed only a “poor performance” with regard to resource productivity. Since 1980 the average yearly increase in the EU-15 amounts to 2.9 % per year. They point out that increasing material productivity is not necessarily associated with a reduction in the overall use of material. Moreover, the authors argue that resource productivity improvements between a factor of 2 and 4 could be possible if highly productive countries are used as benchmarks. They consider the lower threshold for resource requirements to be around 12 t/cap, which is slightly lower than in other studies. Also, they found that the competitiveness of economies is positively related to their resource productivity. Visual inspection of the graphics of the publication suggests that differences in resource productivity have increased between 1992 and 2000, which is an indication for the absence of σ-convergence. Moreover, the authors argue that the highly productive countries are not necessarily exhibiting the strongest dynamics of improvement. For example, Ireland was able to improve its resource productivity dramatically from a rather low level.

Bleischwitz and Bringezu (2011) argue that by 2005 material productivity has improved in Europe as a general trend. The best performing countries included the UK, France, Malta, Italy, Belgium and Luxembourg, Germany, and Sweden. Performance was least strong in Bulgaria, Romania, Estonia, and the Czech Republic. The differences between the individual countries amount to a factor of 17. The EU-27 average of material productivity corresponds to 1700 USD/t DMC. In 2005 it was 3000 UDS/t in Switzerland, in Japan 2600 USD/t, and in Norway 2000 UDS/t. The USA, Canada, Australia, and New Zealand showed a lower material productivity than the EU-27, but this was still higher than the EU-12. Growth in material productivity was highest in the new member states. Between 1992 and 2005 Latvia, Poland, and the Czech Republic were able to realize growth rates of more than 50 %, and Estonia realized an improvement of 122 %. In the UK, Slovakia, Germany, France, Sweden, Ireland, and Belgium and Luxembourg, material productivity grew by 30–50 %. Interestingly, differences in the material productivity in the old and the new member states did not change significantly since the early 1990s. The EU-12 average was 41 % of the EU-15 average in 1992 and only 43 % of the EU-15 average in 2005. Also the material productivity in the EU-12 remained below the average of the EU-27. The high rates of improvement in material productivity of some of the new member states might indicate some form of β-convergence. With regard to σ-convergence, this publication does not allow speculations. The authors also argue that in the EU-15 labor productivity growth was considerably stronger than material productivity growth. Regarding general explanatory factors for differences between structurally similar countries (in terms of levels of industrialization and income), Bleischwitz and Bringezu propose the analysis of socioeconomic variables and innovation systems such as construction activities, structure of energy systems, and effects of imports and international trade.

Resource use and resource efficiency in Asia between 1985 and 2005 was examined by Giljum et al. (2010). Their analysis included the Arab countries. The sample consisting of Bahrain, Bangladesh, China, India, Indonesia, Israel, Japan, Jordan, Malaysia, Oman, Pakistan, the Philippines, Qatar, Republic of Korea, Saudi Arabia, Singapore, Sri Lanka, Thailand, and Turkey makes up 90 % of overall "Asian" GDP. The average Asian DMC/cap increased from 3.7 tonnes/cap in 1985 to 5.5 tonnes/cap in 2005, which is still below the global average of 8.5

tonnes/cap. The authors argue that in poor countries DMC/cap is very low and can even fall if it coincides with high population growth, such as in Bangladesh or the Philippines. On the other hand small, rich, and/or oil-exporting countries like Bahrain, Qatar, Oman, and Singapore show a very high per capita consumption, for example, reaching up to 45 t/cap in Bahrain in 2005. In general, out of this sample, Bahrain, Qatar, Singapore, Oman, Japan, Malaysia, Republic of Korea, Israel, and Saudi Arabia lie above the global average of 8.5 t/cap, whereas the remaining countries lie below it. Only Turkey, Indonesia, Thailand, and China can be found between the global average and the Asian average of 5.5 in 2005. Jordan, the Philippines, India, Pakistan, Sri Lanka, and Bangladesh lie below the Asian average. The strongest upward dynamics can be found in Bahrain, Qatar, Malaysia, and Oman in the upper part and Turkey, Indonesia, Thailand, China, and Jordan in the lower part. Giljum et al. confirm the intuitive assumption that poor countries consume mostly biomass and nonmetallic minerals, whereas richer countries have different production and consumption patterns that are reflected in rising shares of fossil fuels and metal ores in overall per capita consumption. Visual inspection of the authors\ graphics seems to indicate σ-divergence in terms of material consumption in Asia as well as a certain trend towards the average of the industrialized countries (15–20 t/cap). At the same time, individually the countries display very divergent trends in per capita material consumption. Therefore, no speculation can be made regarding β-convergence of DMC. Material productivity (GDP/DMC) does not show a strong upward trend in Asia in the years between 1985 and 2005, as strong economic growth was accompanied by an almost equally strong increase in material consumption. For many Asian countries economic development is coupled with material consumption. In this context three different groups of countries emerge: firstly, countries undergoing rapid industrialization with fast-growing GDP in connection with a strong increase in material use followed by a stabilization as more advanced technologies are implemented and the service sector is enlarged (the Republic of Korea is an example of this first category); secondly, resource extracting countries which have increased their material consumption without similar positive impacts on GDP, for example, Malaysia and Indonesia; and finally, poor countries with large populations which did not display significant change in either GDP or material consumption. Average material productivity increased from 490 USD/t (in constant prices 2000) in 1985 to 530 USD/t in 1995 and decreased again to 520 USD/t in 2005. The global average material productivity increased from 500 UDS/t in 1985 to 640 USD in 2005 and thus outperformed Asian development. Again, variation in material productivity is very high in Asia, ranging from 2400 USD in Japan to 140 USD in Indonesia. Japan has an extraordinarily high material productivity even in comparison to the more productive Asian economies. In Asia, only Singapore, Israel, Republic of Korea, Qatar, and Saudi Arabia were above the global average in 2005, whereas all remaining countries (except for Bahrain) lay considerably below both global and Asian average material productivity. In the upper part, all countries were able to realize a positive development of material productivity, but a common level was not discernible. In the lower part the patterns are more mixed and no clear picture emerges. However, the majority of countries were able to improve their performance, albeit at different levels and in many cases development of material productivity lagged very much behind economic development. The authors interpret this pattern as "a phase in the longer transition process from an agricultural-oriented profile to an industry-oriented profile" (Giljum et al. 2010, p. 22). Analyzing the graphics of this publication visually indicates that the differences between the most productive and the least productive country have increased in time, which might be a sign for σ-divergence. Speculation about β-convergence is very difficult without a closer look at the underlying data. Generally, the authors argue that so far the criteria for sustainability, namely, high levels of resource productivity and development as well as low per capita resource consumption, has not so far been achieved by any country. Giljum et al. see very similar determinants of material productivity on a global level as Bleischwitz and Bringezu (2011); they identify the economic structure of a country, the resource endowments, and the international trade patterns as relevant factors.

Dittrich et al. (2011) examine resource use and resource efficiency in emerging economies over the years 1985–2005. They group 16 emerging economies according to their prominent development strategy since 1985 into resource-based emerging economies such as Algeria, Argentina, Brazil, Chile, Morocco, Russia, and South Africa; economies with a strong focus on industrialization ranging from basic industrialization to advanced industrialization such as China, Costa Rica, Malaysia, Mexico, and the Republic of Korea; and economies based on services like tourism- or financial- or knowledge-based industries such as Egypt, the Seychelles, Barbados, or India. The authors argue that the different development strategies also correspond to certain typical patterns in resource use and resource productivity. In comparison with industry- or service-based strategies, resource-based economic development strategies tend to go hand in hand with higher resource consumption per capita as well as lower resource efficiency and are less dynamic in terms of improvements in resource efficiency. The authors show that industrializing or service-oriented countries like China, the Republic of Korea, or India generally import resources, whereas resource-based countries primarily export resources. They note that absolute amounts of exports or imports strongly depend on the volume of the material in question, for example, petroleum exports are naturally more bulky than copper exports. The authors also highlight the fact that if more emerging economies follow the path of industrialization or service sector development, fewer countries will need to support the global demand for material which will lead to an increase in environmental pressures in these countries. In terms of material use, the emerging economies more than doubled their DMI and DMC since 1985. Average per capita DMC in the emerging economies corresponded to 6.5 t/cap in 2005 increasing from 4.4 t/cap in 1985. It seems evident that resource-based countries display a higher DMC/cap than industrializing or service-oriented countries. A reason for this is that with DMC and DMI, only direct material flows are considered. Also, the high levels of resource consumption in resource-based countries stem from the fact that many of those countries are very large and require considerable amounts of material to build and maintain the infrastructure necessary for extraction and export of material. For industrializing and service-based countries, DMC appears to increase with income. Also in most Latin American countries, the Republic of Korea, South Africa, and Russia, DMC was above world average and close to the average for industrialized countries (15–20 t/cap) in 2005. Regarding the development of DMC over time, in resource-based countries (except for Chile) DMC increased only slightly; in some cases it stayed more or less constant or even declined. In the case of Chile, the exploitation of copper is the reason for its very high per capita material consumption values. When copper is extracted, its copper content is around 1 %; however, for export the copper is concentrated or refined. The remaining 99 % or extracted materials are counted as domestic extraction, which explains the very high DMC values. The opposite is true for industrializing or service-based countries; most of them experienced increasing DMC. This study confirms the use patterns found in Giljum et al. (2010), namely, that poorer countries consume mostly biomass and nonmetallic minerals and that this composition changes in line with increasing income.

A look at their graphical representations indicates that differences between the country with the highest DMI and the lowest DMI increased between 1985 and 2005, indicating the absence of σ-convergence. If the country with the second highest DMC is considered, the pattern is not so clear. Regarding patterns of β-convergence, there does not seem to be any indication of countries with a low DMC catching-up with countries with a higher DMC. However, in the upper part of the country sample, a group consisting of South Africa, Mexico, Russia, Barbados, the Republic of Korea, and Brazil appears to tend towards a similar level of DMC.

Material productivity estimated in constant UDS of the year 2000 with PPP (purchasing power parity) yields different results from material productivity without considering PPP. This is due to the fact that GDP based on constant 2000 USD market exchange rates (MER) increased less strongly than GDP based on PPP values. Material productivity (PPP) increased by a factor of 2.7 between 1985 and 2005, whereas material productivity (MER) increased only by a factor of 1.4. Average material productivity improved from 200 UDS/t (constant prices) in 1985 to 280 USD/t in 2005. It therefore increased faster than the global trend, which improved by 28 percentage points between 1985 and 2005. Variation between different groups of countries is discernible. Resource-based countries seem to be less productive than industrializing or service-oriented countries. Within the industrializing countries, more advanced countries (in terms of technology) are more productive than countries in an earlier stage of industrialization. Again, it is argued that low changes in productivity can be attributed to a phase in the process of transition. Also the lower material productivity of emerging economies might be a result of exporting materially intensive industries from the industrial countries. The patterns of development of material productivity are mixed; some countries experienced rising productivity rates, others stagnated, and still others diminished their material productivity. Overall the emerging countries are still very far from productivity rates displayed in the EU-15, for example, (1700 USD/t in 2004) or Japan (2400 USD/t in 2005).

A look at the graphics of this publication indicates that differences between the most productive economy and the least productive economy have increased between 1985 and 2005. Moreover, the graphics suggest that emerging economies were on average able to realize higher productivity rates than the global average. Their position relative to the global leader cannot be assessed by means of this overview. Within the emerging economies no clear pattern with regard to possible convergence towards a common level or similar development patterns of material productivity can be discerned.

Kovanda et al. (2012) provides an example of a case study type of country analysis which can provide detailed information on the reasons for the development of the aggregate indicators. The authors examined the Czech Republic, Germany, and the EU-15 in a detailed analysis, looking at the underlying material categories of the DMI and TMR. They found that DMI and TMR did not display an increasing or decreasing trend between 1991 and 2004. However, material intensity decreased which implies an increased efficiency in the production of goods and services. Their analysis also revealed that the structure of the Czech Republic became more similar to the structure of Germany and the EU-15. This can be seen on an aggregate level through similar overall material and resource use per capita but also in terms of the direct use of biomass, the disproportionate use of brown coal, a similar level of construction mineral use, a high dependency on metal resources for manufacturing, as well as the tendency to shift environmental pressures abroad by importing less ore and base metals. The authors attribute this to a process of convergence in production technologies and use patterns of households and industry. The convergence of production technologies might be a consequence of shifting the production of western European companies to Central and Eastern Europe for cost savings. Therefore, the authors predict that given the current trends that the Czech Republic will achieve German/EU-15 levels of material intensity over the next 20 years or so.

Besides the studies on groups of countries, a range of individual country studies have been conducted. For a list of studies on European countries, see Bringezu et al. (2004). For the rest of the world see, for example, Eisenmenger et al. (2005) for Saudi Arabia, Switzerland, and the USA; Giljum (2004) for Chile; Gonzales-Martinez (2007) and Gonzales-Martinez and Schandl (2007) studied Mexico; Russi et al. (2008) studied Chile, Ecuador, Mexico, and Peru; Schandl and West (2010) examined the Asia-Pacific region; Lanz (2008) for India, and Chen and Qiao (2001) studied China. However, newer datasets now include most of the countries in the world, and their data is more easily comparable as it stems from only one source, and there are no variations in the methods of calculation.

Summing up, it becomes clear that studies on material use and the efficiency of material use focus on the description of the data. For the debate about sustainability, the levels of material input or consumption are a central concern. Also, the level of material productivity or intensity is, respectively, examined and compared internationally. In these international comparisons large differences between both material use and material productivity have been detected. Another central concern of sustainable development is the decoupling of material use from economic growth. Naturally, this is a question that has received much attention in the ongoing debate.

The question of whether material productivity development follows any regular patterns bears interesting and important implications for the development of material use as well as sustainable development; however, it has not yet been analyzed. This dissertation aims to contribute to closing this research gap.

Part II
Empirical Analysis of Material Productivity Convergence

Chapter 7
Research Question

The second part of this dissertation analyzes material productivity development dynamics between 1980 and 2008 in order to explore empirical regularities in material productivity development over time. This part starts with the presentation of the research question in this chapter, then the data and first descriptive statistics are presented, and a descriptive convergence analysis is conducted in Chap. 8. In Chap. 9 material productivity convergence is examined, and Chap. 10 discusses the results and proposes further research areas.

Around 20 years after the first Rio summit on sustainable development, the insight that the natural resources of the world need protection is a central idea not only of environmental policy but also in economic and competition policy, for instance, in the context of the OECD's Green Growth Strategy or the UNEP's Green Economy Report (OECD 2011c; UNEP 2011b). In terms of environmental policies, individual countries as well as organizations like the EU have adopted specific sustainability policies. On a European level these include EUROPE 2010, the Thematic Strategy on the Sustainable Use of Natural Resources or the strategy on sustainable development, as well as the Flagship Initiative "a Resource Efficient Europe" which includes the Roadmap to a Resource Efficient Europe (European Commission 2010, 2011a, b; Commission of the European Communities 2005). A core aim of these strategies is the promotion of an efficient use of resources. In order to measure progress in this field, to provide signaling, and to be able to set policy aims, a set of indicators, comprising one lead indicator "resource productivity" and complementary indicators for water, land, and materials use and carbon, have been (provisionally) formulated (European Commission 2011b). The lead indicator "resource productivity," defined as the ratio of GDP to domestic material consumption (DMC), is nothing other than one of the material productivity indicators, namely, domestic material productivity, proposed by Eurostat (2001a) and the OECD (2008b, c).

Data availability for material productivity was poor in the beginning; however, since the publication of the dataset *Material flow Database* by SERI et al. in 2012 on http://www.materialflows.net, this has improved considerably. Even before material flow data was easily available, numerous studies have examined the

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development of material flow indicators, mainly direct material input, direct material consumption, total material input, and total material requirement but also material productivity and physical trade balances, for instance, Bringezu et al. (2004), Dittrich (2010), Moll et al. (2005), SERI Sustainable Europe Research Institute (2009), and Weisz et al. (2006). These studies examine the development of these indicators over time and/or for individual countries. However, the studies often examine the data at one point in time or in larger intervals of several years and not as complete time series. Additionally, although some studies analyzed specific questions, like the existence of an environmental Kuznets curve (Bringezu et al. 2004), decoupling (van der Voet et al. 2005), or the relation between material productivity and competitiveness (Bleischwitz et al. 2007), just to name a few, many of the studies focus on the description of development patterns alone. To the best of the authors' knowledge, so far no formalized statistical-econometrical analysis of the development patterns of material productivity has been conducted in order to detect possible empirical regularities in the process of material productivity development.

This dissertation aims at closing this research gap. Besides a description of material productivity development in the OECD and BRICS countries between 1980 and 2008, the question whether material productivity development exhibits convergence patterns over time is examined in this dissertation. Thus, it investigates whether empirical regularities that have been found to exist for other variables like per capita income or labor productivity, for example, in Abramovitz (1986), Mankiw et al. (1992), Evans (1998), Färe et al. (2006), and Margaritis et al. (2007), or energy productivity, for instance, in Miketa and Mulder (2005) or Mulder and de Groot (2007), can also be identified for material productivity.

The motivation for an analysis of material productivity convergence is twofold: firstly, insights into material productivity development patterns can contribute to the understanding of TFP growth. So far, the empirical studies designed to understand productivity growth have mainly focused on labor and TFP growth analyses. As the importance of energy as a crucial production factor received increasing attention, energy productivity developments and its determinants came into focus (Mulder 2005, p. 11) and a number of studies were conducted, for instance, Mulder and de Groot (2007) or Miketa and Mulder (2005). In recent years increasing awareness has been paid to the importance of materials in general in the production process and their role for international competitiveness, represented, for instance, in the public debate about "critical minerals" or "rare earths." Therefore, an analysis of material productivity convergence can provide insights not only into the efficiency with which different economies produce output but also into possible empirical regularities of material productivity development. The theoretical foundation for convergence analysis of productivity lies in endogenous growth theory. For example, models of endogenous growth such as the Schumpeterian model of Aghion and Howitt described in Sect. 4.1.2 imply convergence of technology growth rates for those countries which are innovating due to technology transfer. Technology can be measured by total factor productivity, and thus, TFP can be expected to show patterns of convergence (club). Dollar and Wolff (1988) have examined TFP convergence and concluded that convergence of TFP levels has been the main source for convergence of labor productivity. It may be possible that a similar relationship exists for TFP and material productivity. Thus, an analysis of material productivity convergence may provide insights into the relationship between material productivity development and total factor productivity. Also, understanding how the single-factor productivities develop can contribute to a better understanding of aggregate productivity (TFP) development.

Secondly, and in the context of this dissertation more importantly, understanding of the presence or absence of MP convergence can contribute to the debate about sustainable development. The fact that higher resource use leads to higher environmental pressures has motivated the adoption of environmental or sustainability policies. One major aim of environmental policy is the decoupling of resource use and economic development. In order to achieve decoupling, the change in material productivity needs to be larger than the change in domestic output. Thus, material productivity developments increasingly become the focus of attention. The study of convergence of material productivity development can provide insights into empirical regularities present in the evolution of MP and is consequently relevant to sustainable development.

Before discussing the implications of convergence and non-convergence of material productivity, the relationship between material productivity and material consumption levels will be clarified briefly. Material productivity is a composite indicator relating gross domestic product and material consumption. As mentioned before, a change in the productivity indicator can be caused by either one of the components or by both. Table 7.1 shows how changes in the two components GDP and DMC are related to changes in material productivity. If GDP remains constant, it is easy to see that material productivity decreases or increases depending on whether material consumption decreases or increases. When GDP increases and DMC decreases, material productivity rises. Similarly, if GDP rises and DMC remains constant, material productivity also rises. It becomes more complex when both GDP and DMC increase: the development of material productivity will then depend on the actual rates of change of GDP and DMC in relation to each other. This means, if GDP increases more strongly than DMC, MP rises; if DMC increases more strongly than GDP, material productivity falls; and if both components increase in proportion, MP remains constant. In the case of a falling GDP, two cases are again intuitive. Material productivity increases if DMC remains constant, and MP decreases if GDP decreases and DMC rises. When both GDP and DMC fall, effective MP development will again depend on the relative changes in both components relative to each other: if both decrease proportionally, MP will remain constant; if material consumption decreases more strongly than GDP, material productivity will rise; and if GDP decreases more strongly than DMC, material productivity will fall. By implication this also means that an increase in material productivity does not automatically imply a reduction of consumption levels. Yet, with all other things remaining equal, an increase of material productivity bears the potential for a reduction in material consumption. Thus, these illustrations of the relations between the development of GDP, DMC, and material

Table 7.1 Relations between GDP, DMC, and MP development

GDP development	DMC development	MP development
GDP constant	DMC increasing	MP decreasing
GDP constant	DMC decreasing	MP increasing
GDP constant	DMC constant	MP constant
GDP increasing	DMC increasing	MP development dependent on actual relationship between growth rates of GDP and DMC
GDP increasing	DMC decreasing	MP increasing
GDP increasing	DMC constant	MP increasing
GDP decreasing	DMC increasing	MP decreasing
GDP decreasing	DMC decreasing	MP development dependent on actual relationship between growth rates of GDP and DMC
GDP decreasing	DMC constant	MP increasing

Source: Own illustration

productivity also suggest that changes in material productivity are determined both by factors that influence GDP and economic growth and by factors that influence material consumption levels and changes.

The presence or absence of convergence of material productivity in its different forms has several implications. Presence of σ-convergence of MP indicates that the variation in material productivity decreases over time; thus, MP performances become less unequal internationally. If σ-convergence is not caused by a falling back of the more productive countries, this implies that less productive countries have been able to improve their MP performance, which will in turn contribute to a more efficient use of resources internationally and possibly to a decoupling of resource use and economic development. Absence of σ-convergence implies that existing inequalities in MP performance remain.

The presence of β-convergence of material productivity implies that less productive countries are able to catch-up in terms of material productivity, by realizing higher growth rates of material productivity, thus improving their MP more strongly than their more productive counterparts. If less productive countries improve their MP, faster additional benefits in terms of efficiency of material use can be realized internationally.

The presence of convergence of MP levels (time-series concepts) can inform to what extent a reduction of absolute material consumption may be possible. Convergence towards high levels of material productivity provides an increased potential for a reduction in global material consumption, if the material productivity gains are not overcompensated in terms of an increased material consumption in subsequent periods. If convergence takes place on low material productivity levels, the potential for a reduction of international material consumption is reduced.

This also implies that generally, non-convergence of material productivity both in growth rates and in levels implies that there is no potential for a reduction of material consumption internationally. In combination with population growth and economic developments, especially in the developing countries, this will lead to substantial increases in material consumption and thus increase environmental pressures.

In short, the understanding of patterns of material productivity development over time and of possible empirical regularities can contribute to the debate about sustainable development, especially if one bears in mind that increases in MP ceteris paribus generate the potential for a reduction in material consumption. An analysis of material productivity convergence can also contribute to the present discussion in several further ways. Firstly, it can provide new insights into the relationship of economic growth to material consumption, also in the light of arising scarcities of some materials. Secondly, recent years have shown increases in material productivity. An analysis of the dynamics of these increases and their spatial distribution may provide interesting insights. Moreover, lack of MP convergence can provide information about the extent to which diffusion of material saving/material efficient technologies takes place. Consequently, it can contribute to better regulation and technology policies. Thirdly, information about convergence processes or their absence can be used for the calibration of macro models, forecasting economic and ecological development, because projections of material consumption depend on the assumptions made about material productivity growth. Insights into empirical regularities and development patterns of material productivity may contribute to increasing the quality of models and forecasts. Fourthly, few quantitative analyses have been conducted on material productivity. Given that the European Union has chosen material productivity as one of its sustainability indicators, a better understanding of the indicator and its development patterns can provide information for political decision-making.

Technically, the examination of material productivity convergence follows the analysis of convergence of per capita incomes. Starting with basic cross-section analysis of the relationship between the initial level of MP and its subsequent growth rate following the analysis of Abramovitz (1986) and Baumol (1986), the analysis continues using regression approaches, both in a cross section and a panel framework following Mankiw et al. (1992) and Islam (1995). It concludes with a convergence analysis using a time-series data structure similar to Evans (1998). As well as depicting the course of the technical development of the convergence analysis, the application of different methods will allow the cross-checking of the results derived from different methods, which will allow clearer inferences about the robustness of the results.

Chapter 8
Data and Descriptive Statistics

Section 8.1 describes the data used in this dissertation which are drawn from the World Bank and from the Global Materialflow Database as well as their limitations. Section 8.2 calculates the descriptive statistics of the data, and Sect. 8.3 conducts a descriptive, graphical analysis of material productivity developments over time.

8.1 Data

This dissertation examines material productivity developments between 1980 and 2008 for the OECD and BRICS countries. The OECD members are Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the UK, and the USA. The newest OECD members are Chile, Estonia, Israel, and Slovenia which all joined in 2010. BRICS is an abbreviation for a group of countries consisting of Brazil, the Russian Federation, India, China, and South Africa. The OECD countries in 2011 contributed around 65 % to global GDP (in 2005 PPP), whereas the OECD predicts that in 2060 China and India alone will contribute around 46 % to global GDP and the OECD's share will decline to 42 % of global GDP (OECD 2012, p. 23). The BRIC country groups (not including South Africa) contributed around 17.5 % to global GDP in 2009 (Eurostat 2012a). As the share of China and India can be expected to rise and other non-OECD countries are expected to increase their 2011 share of 11 % of global GDP by 2060 to 12 % of global GDP (OECD 2012), the relevance of the BRICS countries can be expected to rise over the next few decades. Thus, at present the country sample under consideration accounts for roughly 80 % of global GDP and this share is not expected to decline in the next decades. Additionally, in the following analysis the so-called transformation economies of the OECD group are sometimes considered as a separate group. In the country sample under consideration, the Czech Republic, Estonia, Hungary,

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Poland, the Russian Federation, the Slovak Republic, and Slovenia comprise the transformation economies. They are considered separately because they as a group experienced similar initial conditions after the end of the Soviet Union and can be expected to have faced similar challenges in the almost two and a half decades since.

The dataset analyzed is composed of several datasets from different sources. The GDP data and the data on the share of the service sector come from the World Bank, and the material flow data is a joint project from SERI (Sustainable Europe Research Institute), the independent researcher M. Dittrich, and the Wuppertal Institute for Climate, Environment, and Energy. Each dataset will be described in more detail.

The GDP data used here is gross domestic product converted to international dollars using purchasing power parity rates so that the data are in constant 2005 international dollars. The data can be found in the International Comparison Program database of the World Bank.[1] For the country sample under consideration here, the dataset is not complete for the full period from 1980 to 2008. This is due to the fact that for all transformation economies included in this analysis, except for Hungary, data are provided from different years at the beginning of the 1990s onwards and no earlier. Also, Irish GDP data starts only in 2000. In order to make the GDP data conform with the material flow data, the GDP data for Belgium and Luxembourg had to be added together to give what appears as Belgium-Luxembourg in the dataset.

The data on the share of the service sector in the respective countries as percentage of total GDP was also obtained from http://www.worldbank.org.[2] The services correspond to the divisions 50–99 of the International Standard Industrial Classification and include value added in the wholesale and retail trade (including hotels and restaurants), transport and government, financial, professional, and personal services such as education, health care, and real estate services as well as bank service charges and import duties. The share of the service sector is calculated as value added; thus intermediate inputs are subtracted from the sum of outputs of the sector. Depreciation of assets or degradation of natural resources is not included. The data can be found in the database for World Development Indicators. Service sector data are missing for Estonia, Greece, and Israel. New Zealand only provides data from 2006, not 2008, and for Poland (1990), the Slovak Republic (1985), Slovenia, and the Russian Federation (1989), the first data available as indicated were used. The data for Belgium-Luxembourg were calculated separately, relating the share of services in the two countries to the combined GDP of Belgium and Luxembourg.

The data on direct material consumption (DMC) are based on the Global Materialflow Database on http://www.materialflows.net by SERI, Dittrich, and the

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[1] Data accessed on http://www.worldbank.org, the International Comparison Program on August 16, 2012.

[2] Data accessed on http://www.worldbank.org, World Development Indicators on September 27, 2012.

Wuppertal Institute for Climate, Environment, and Energy. The dataset provides data on DMC for all countries under consideration for the period between 1980 and 2008. The data in this dataset are the result of an integration of SERI's database on resource extraction and M. Dittrich's database on resource trade (Dittrich et al. 2012). The database on material extraction is based on international statistics from agencies such as the International Energy Agency, the United Nations Food and Agriculture Organization, or the US and British Geological Surveys, which provide data on fossil fuels and biomass as well as metals and industrial minerals. The owners of the database explain that data quality varies for the different types of materials and while it is quite good for the extraction of fossil fuels and metals, it is less so for biomass especially in poor countries, where actual biomass extraction might be larger than estimated. Statistics about mineral use lack quality in all the countries examined. Therefore, the extraction of construction minerals was estimated using a method in which the physical production of cement and bitumen is used to estimate overall levels of extracted minerals, particularly limestone, sand, and gravel. If data on cement and bitumen production were not available, per capita income has been used as a proxy, assuming that demand for construction minerals rises as per capita income rises; this may lead to over- or underestimation of the exact amounts of mineral extraction in some countries. More details on the compilation of each material class can be found in the technical report by SERI (2010).

The database on the resource trade, developed by M. Dittrich in cooperation with the Wuppertal Institute, is based on UN Comtrade data and includes global accounts of imports and exports in physical (mass) units (Dittrich et al. 2012). Missing mass values in the UN Comtrade dataset were filled in by analyzing regularities between monetary and mass values of product groups and using these regularities to extrapolate from monetary values to mass values. This procedure was conducted step-by-step from levels of low aggregation to levels of higher aggregation. Direct trade flow values were corrected if identified as major outliers by adjusting with regard to global prices, amounts of global imports and exports, bilateral trade data if available, as well as international sector statistics. Missing trade data reports were estimated by extrapolation, bilateral data of trade partners, and/or sectoral, national, and international trade statistics in order to calculate aggregate regional and global values. Dittrich et al. (2012) argue that the UN Comtrade statistics are good with respect to differentiation and reliability for the OECD and Latin American countries, but for the remaining countries, the quality is mixed. And that generally, trade statistics after 1995 are more differentiated and complete than earlier data. More details on the compilation of the data and possible limitations can be found in Dittrich (2010).

For the Global Materialflow Database, the two previously described datasets were combined. This database provides information on material extraction, trade, and consumption.[3] The GDP data obtained from the World Bank and the DMC data from the Global Materialflows Database were used to calculate domestic material

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[3] Data accessed on http://www.materialflows.net on August 31, 2012.

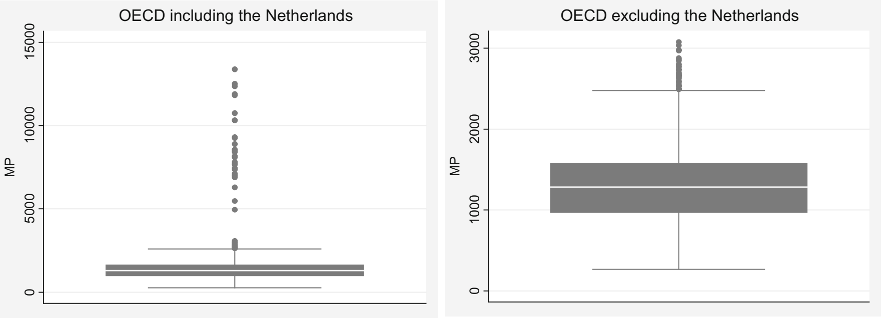


Fig. 8.1 Boxplots of material productivity in the OECD with and without the Netherlands. *Source*: Own calculation based on Global Materialflow Database (2012)

productivity by dividing GDP by DMC. The quality of the database is ensured through regular data checks and cross-checks with other institutions working on similar data such as the US and British Geological Survey and has been recognized internationally leading to the application of the data in various studies and projects (Eurostat 2012b).

The first descriptive analysis of the data on material productivity from the Global Materialflows Database showed that the data from the Netherlands greatly influenced the picture as a whole, and results are significantly altered depending on whether the Netherlands are included in the sample considered or not. When the OECD data including the Netherlands are compared with OECD data excluding it, one can observe that the maximum value identified in the dataset is around four times higher rising from around 3076$/tonne to around 13.375$/tonne when the Netherlands are included. Consequently, the range, variation, and standard deviation also display significantly higher values. This difference between the values seems quite extreme. The picture becomes even clearer when the boxplots of material productivity for the OECD including and excluding the Netherlands are compared in Fig. 8.1. The figure shows that a great part of the outliers of the distribution can be attributed to the Dutch data.

Also, comparison of the Dutch data from this dataset with Dutch data from other publications, for instance, Bleischwitz et al. (2007), European Environment Agency (2010), or Eurostat (2011), showed that in other publications the data for the Netherlands did not display such extreme values in comparison to other countries' data. Dittrich (2010) explains that in the construction of the data, mass values provided by the UN Comtrade could generally not be corrected due to the size of the database, and it is therefore possible that implausible values or outliers are included in the data as a consequence of transmission errors between the agents included in the process of compiling the data. The dataset only provided aggregated data, so that no analysis of individual material groups and the plausibility of their size could be conducted. Due to the fact that other studies have not found the Dutch data to display such extremes as in the case at hand, the data for the Netherlands were excluded from the subsequent analysis as it can be assumed that these data might be driven by some extreme values at a lower level of aggregation.

8.2 Descriptive Statistics

To get a first overview of the main characteristics of the data on material productivity in the OECD and BRICS countries, descriptive statistics were computed and analyzed.

First, the descriptive statistics for the full sample are examined. The mean material productivity is around 1212 international USD (2005 in PPP) per tonne of material, and the median material productivity lies at around 1175 international USD/tonne. The difference between the highest and the lowest value of material productivity in this sample amounts to 2902 international USD/tonne, and the standard deviation is around 576 USD/tonne (see Table 8.1).

Secondly, the common descriptive statistics for the different groups were calculated (see Table 8.2). The OECD countries generally display a higher mean of material productivity. As was to be expected, both the BRICS and the transformation economies display lower average material productivity. Also it can be observed that in the transformation economies, the level of material productivity is closer to the OECD level than to the BRICS level. Not surprisingly, the statistics show that the country with the lowest material productivity can be found in the BRICS group and the country with the highest material productivity is in the OECD.

Next, the distribution of the data was examined in order to draw inferences about the distribution of the data. First, the skewness of the distribution is analyzed. The data for the full sample shows that the distribution is skewed to the right (positive skew), which is indicated by the value 0.6114. This implies that the right tail of the distribution is longer than the left tail. Next, the kurtosis indicates how peaked the distribution is. The standard normal distribution is characterized by a kurtosis of 3.0. The distribution here shows a kurtosis of 3.189; therefore, the peak of this distribution can be expected to be similar to that of a normal distribution. Combining this information in a histogram and a kernel density plot, these findings are visualized and the skewness to the right becomes visible (Fig. 8.2).

The characteristics of the different subgroups, namely, the OECD countries, the BRICS countries, and the transformation economies, can also be described by means of boxplots (see Fig. 8.3). These can be used to visualize the median, and the 25 % and 75 % quintile, i.e., 50 % of all data points, lie within the box. Also, they display outliers, which can be found above the 95 % percentile. The boxplot for the full sample naturally resembles the histogram and kernel density plot of the data. Just like the latter, the boxplot shows that the distribution is skewed to the right. This can be concluded from the fact that the 95 % percentile, i.e., the upper whisker, is longer than the lower 5 % percentile whisker. If the skewness was more

Table 8.1 Descriptive statistics OECD and BRICS

Country group	Mean	Median	Variance	Standard deviation	Min	Max	Range
OECD and BRICS	1,212.587	1,175.86	3,32519.3	576.6449	174.69	3,076.69	2,902

Source: Own calculation based on Global Materialflow Database (2012)

Table 8.2 Descriptive statistics for subgroups of the full sample

Country group	Mean	Median	Variance	Standard deviation	Min	Max	Range
OECD	1,317.307	1,284	298,552	546.3991	265.77	3,076.69	2,810.92
BRICS	547.2604	555.5	36,008.57	189.7592	174.69	1,060.71	886.02
Transformation economies	1,026.092	971.58	94,075.69	306.7176	491.81	1,830.7	1,338.89

Source: Own calculation based on Global Materialflow Database (2012)

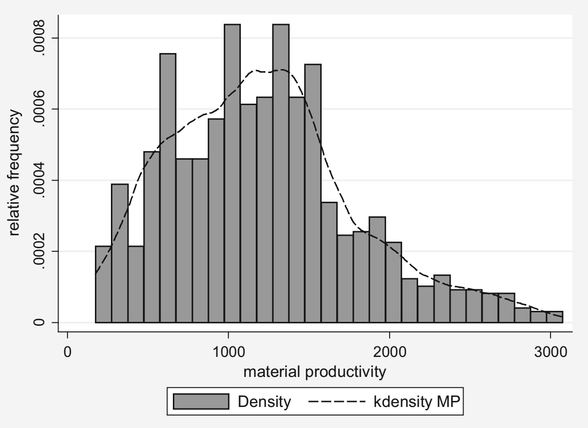


Fig. 8.2 Histogram and kernel density plot: material productivity OECD and BRICS. *Source*: Own calculation based on Global Materialflow Database (2012)

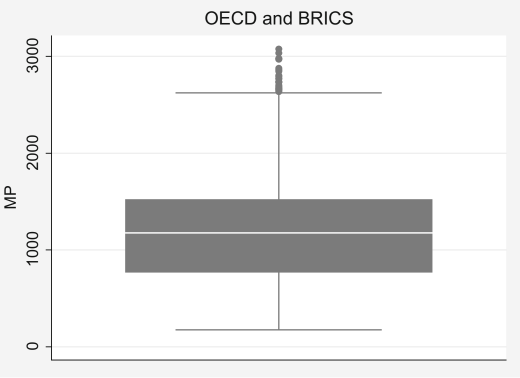


Fig. 8.3 Boxplot material productivity OECD and BRICS. *Source*: Own calculation based on Global Materialflow Database (2012)

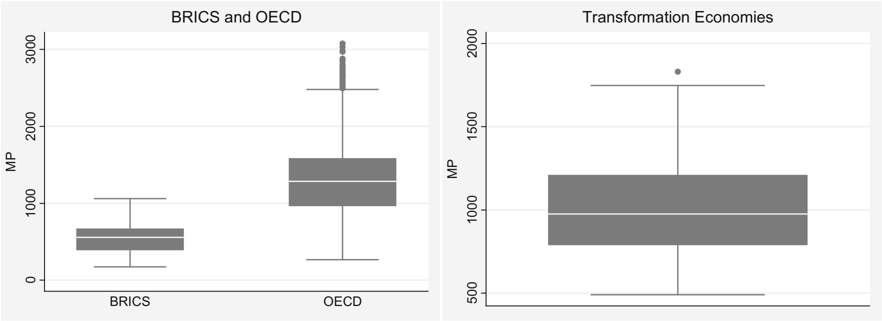


Fig. 8.4 Boxplot material productivity OECD and BRICS and transformation economies. *Source*: Own calculation based on Global Materialflow Database (2012)

pronounced, one could observe that the median, represented by the line within the box, is slightly moved to the bottom of the box, also indicating a right skewness. The boxplot also allows identification of a few outliers above the 95 % percentile whisker.

In Fig. 8.4 the boxplots of the different subgroups of the overall sample, namely, the OECD countries without the transformation economies, the BRICS countries, and the transformation economies, can be found. One can see that the BRICS countries and the transformation economies have basically no outliers and that their distributions are also slightly skewed to the right, again indicated by the length of the whiskers which implies that there are more data points above the median than below.

The development of material productivity over time is analyzed next. Figure 8.5 shows how the mean of log material productivity over all countries, the log MP of the most productive country, and the log MP of the least productive country developed over time. The log transformation of the variable was chosen as it visually displays the tendency more clearly than absolute values do; also in log transformation the growth rates of MP can be read from the slope of the lines. From the steepness of the slopes, one can conclude that both Switzerland, the most productive country, and China, the least productive country, grew faster than average material productivity. Moreover, while the distance between Switzerland and the mean of material productivity seems to remain rather constant over time, China has been able to shorten the distance to the mean as well as to Switzerland, which indicates that China was able to catch up with the more productive countries by realizing higher growth rates.

The analysis of average material productivity in the different subgroups over time in Fig. 8.6 shows that material productivity grew significantly in all three subgroups since 1980. There have been periods of slower growth of MP or even decreasing MP. However, apart from a common dip in the mid-2000s, other common developments are hard to make out. Since their inclusion in the data in 1995, the transformation economies seem to have been able to move closer towards

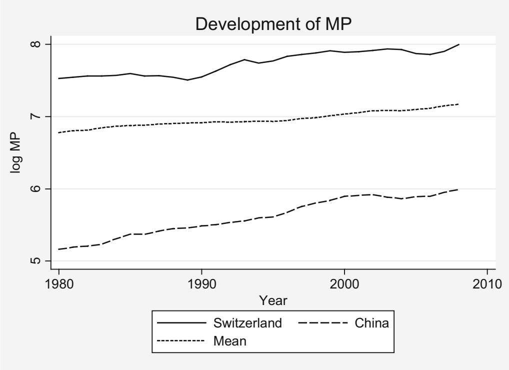


Fig. 8.5 Development of material productivity: most productive, least productive, and mean. *Source*: Own calculation based on Global Materialflow Database (2012)

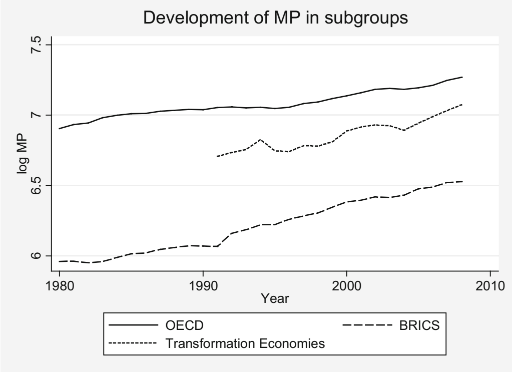


Fig. 8.6 Development of mean MP in subgroups. *Source*: Own calculation based on Global Materialflow Database (2012)

the mean of the OECD countries, i.e., they seem to be catching up. The BRICS countries also have been able to shorten the distance to the OECD countries, especially since the 1990s. However, the BRICS countries' growth in material productivity is not as pronounced as in the transformation economies, a fact that can be concluded from comparing the slopes of the series.

Figure 8.7 shows how the material productivity of individual countries developed, independently of their starting levels. In order to visualize this, an index is constructed in which the value for the year 1980 is set to 100. The material productivity development from 1980 onwards can then easily be compared for the different countries. For the transformation economies the year 1995 was chosen as starting year for the index as complete data is only available since then. One can observe one major difference between the different development paths: while a large group of countries displays a constant growth in material productivity, a smaller group of countries does not seem to be able to realize growth of a similar scope. These countries include Brazil, Chile, Greece, Israel, Korea, Mexico, Portugal, Spain, Turkey, and to a lesser extent Denmark and the Republic of South Africa. For most of the transformation economies, a constant growth of material productivity since 1995 can be observed. The slope of their MP development seems to be less steep, but this is due to the fact that their base year is 1995 and not 1980. As Table 8.3 shows, if the material productivity growth between 1995 = 100 and 2008 is considered and ranked, the transformation economies, printed in italics, can all but one be found in the upper half of the growth performance.

Further information about how material productivity in 1980 and 2008 are related can be drawn from correlation analysis. The correlation between the level of MP in 1980 and the level of MP in 2008 equals 0.7327, indicating a rather strong correlation. This means that the level of MP in 1980 and 2008 are closely related, or they vary together. From a positive correlation coefficient, one can expect that a high level of MP in 1980 will be related to a high level of MP in 2008 and a low 1980 level will be related to a low 2008 level.

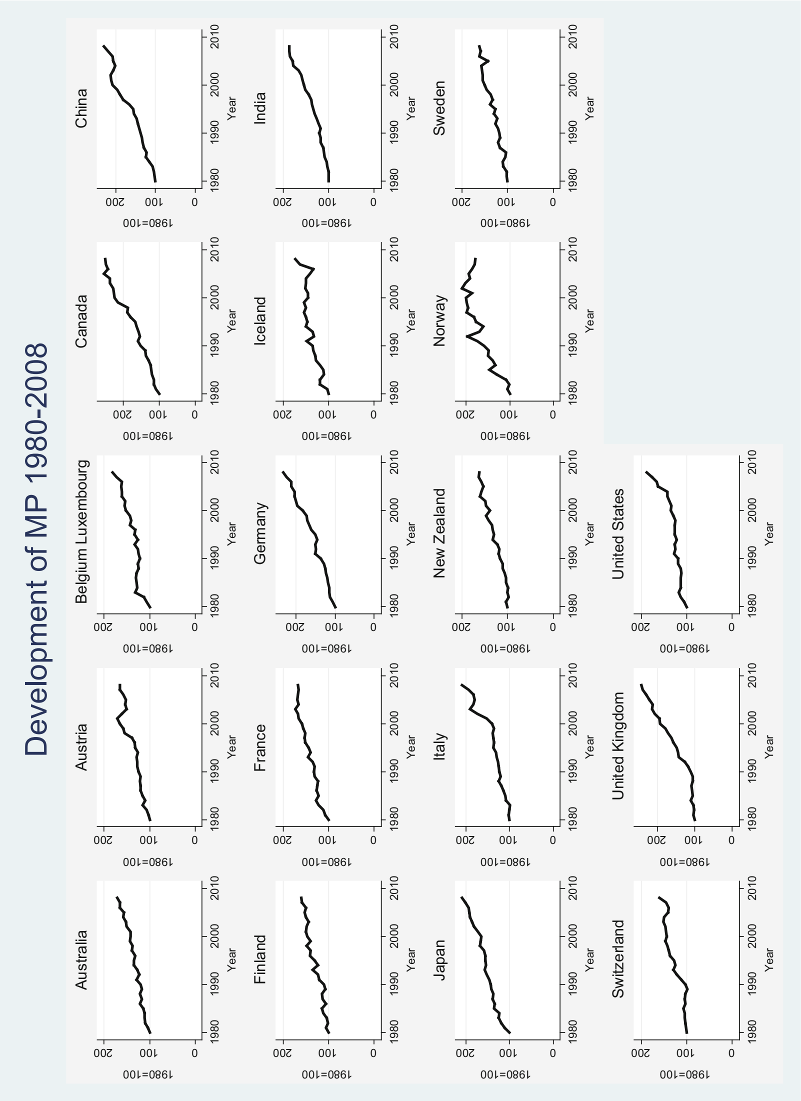
For the correlation between the starting level of MP in 1980 and the growth rate of MP, a negative correlation of −0.2501 was identified. Thus, a high level of MP in 1980 is associated with a low level of MP growth, and conversely, a low level of MP in 1980 is related to a high level of MP growth, and an increase of the starting level of MP will decrease the subsequent growth of MP. This finding is in general in line with the idea of β-convergence, i.e., that richer/more productive countries realize smaller growth rates than poorer/less productive countries.

It has to be noted, however, that the correlation analysis suggests that high growth of MP does not necessarily also lead to a higher level of MP in the future. One possible explanation may be that while less productive countries are able to realize higher growth rates, these growth rates are not high enough to actually catch up with the level of the initially more productive countries. A more detailed investigation of the development patterns of material productivity may therefore prove fruitful.

Summing up, the descriptive statistics show that the development of material productivity between 1980 and 2008 differs strongly between countries and country groups such as the OECD and BRICS. Moreover, the differences between the least productive country and the most productive country in the sample have narrowed. And finally, the correlation analysis yielded that low MP growth over time is correlated with a high initial level of material productivity in 1980 and vice versa as well as that MP in 1980 and 2008 is closely correlated so that a high level of MP in 1980 is related to a high level of MP in 2008. Next, descriptive analysis is used to examine possible convergence or divergence patterns systematically by means of graphics.

8.3 Descriptive Analysis

Possible patterns of convergence or divergence of material productivity can be examined by means of descriptive analysis in a more specific way by looking systematically at the development of the mean and the standard deviation of different subgroups [see Mayer-Foulkes (2010)]. Firstly, the evolution of the standard deviation can provide first indications with regard to the presence of


Development of MP 1980-2008
Australia
Austria
Belgium Luxembourg
Canada
China
Finland
France
Germany
Iceland
India
Japan
Italy
New Zealand
Norway
Sweden
Switzerland
United Kingdom
United States
1980=100
Year
0
100
200
1980
1990
2000
2010

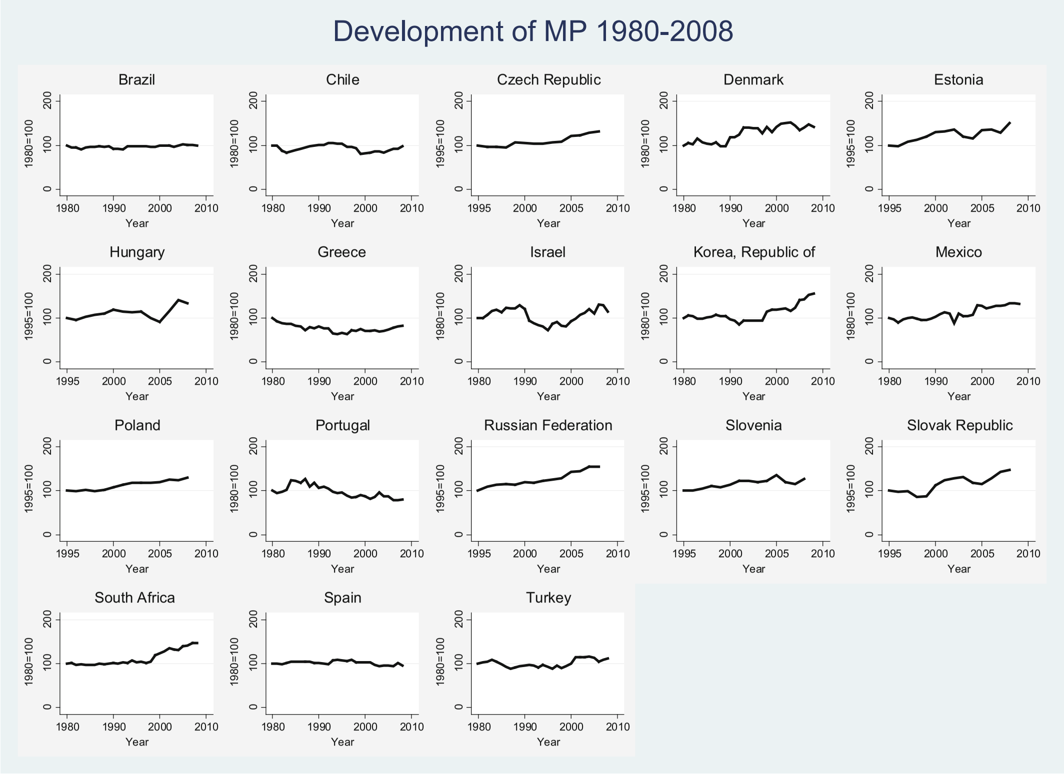


Fig. 8.7 Development of material productivity: individual countries. *Source*: Own calculation based on Global Materialflow Database (2012). Excluded: Ireland

Table 8.3 Index MP growth 1995–2008

Country	Growth	Country	Growth	Country	Growth
Republic of Korea	64.2133	India	39.7951	Greece	23.8852
UK	63.4335	Belgium Luxembourg	36.4026	Finland	22.0562
Israel	58.9485	Japan	33.7866	Turkey	21.3499
Russian Federation	*55.2698*	*Hungary*	*33.2244*	Mexico	19.5352
Germany	54.0806	*Czech Republic*	*31.2075*	Iceland	18.9114
Italy	51.7748	*Poland*	*29.9689*	France	16.7162
Canada	50.3383	Sweden	28.1058	Denmark	1.496
Estonia	*50.2807*	Australia	26.6294	Norway	1.493
USA	48.931	*Slovenia*	*26.4814*	Brazil	1.473
Slovak Republic	*47.2457*	Austria	26.1904	Chile	−5.85281
China	46.3134	New Zealand	25.4084	Spain	−10.44597
South Africa	42.7568	Switzerland	25.3885	Portugal	−5.61121

Source: Own calculation based on Global Materialflow Database (2012)

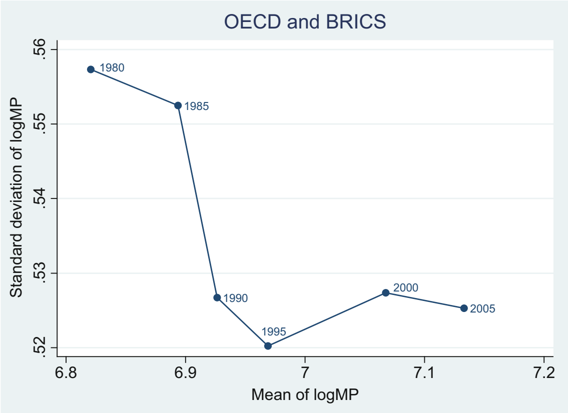


Fig. 8.8 Development of SD and mean full sample. *Source*: Own calculation based on Global Materialflow Database (2012)

σ-convergence. Secondly, the evolution of the mean of MP can indicate material productivity development over time. Figure 8.8 shows the development of the standard deviation and the mean of material productivity in 5-year intervals and one 4-year interval between 2005 and 2008 for the full sample. For the full sample a decline in the variance of MP can be identified; thus, the inequality within the whole OECD and BRICS group decreased over time. Although a slight increase in variation can be observed starting in the quinquennium of 1995, this increase however does not overcompensate previous improvements. Moreover, for the whole period between 1980 and 2008, a steady increase in average material productivity can be observed. Thus, the group as a whole was able to improve its material productivity performance continuously.

The results of the full sample are altered considerably if the development of the individual groups is considered. Figure 8.9 shows how the standard deviation (SD) and mean of material productivity developed in the different subgroups over time. The mean and standard deviation were calculated for 5-year periods, for

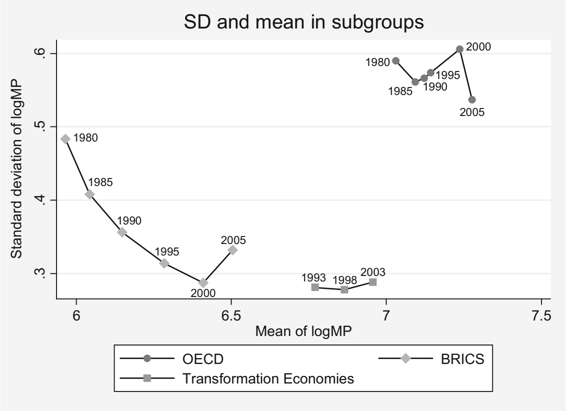


Fig. 8.9 Development of SD and mean in subgroups. *Source*: Own calculation based on Global Materialflow Database (2012)

example, the data point labeled 1980 stands for the standard deviation between 1980 and 1984 and the mean between 1980 and 1984.

However, as the 28-year period for which the data is available cannot be divided into six full 5-year periods, the last period from 2005 to 2008 is only 3 years long for the OECD and BRICS countries. The transformation economies' data starts in 1993[4]; therefore, the 5-year periods end in 2007.

For the OECD countries an overall reduction of the standard deviation can be observed; although the SD is higher than in the other groups, this can be interpreted as σ-convergence. In the years 2000–2004, the standard deviation increased compared to previous values, indicating that the variation in MP in the OECD increased in that period. The values for 2005–2008, however, are again in line with the previous trend before 2000. Also, the mean of material productivity increased constantly over time, which indicates that the OECD countries were able to improve their material productivity constantly over the whole period between 1980 and 2008, although in some 5-year periods the improvement was more pronounced than in others. Overall it seems that between 1985 and 1999 there was very little material productivity development in the OECD. Little change can be found in both the mean and SD of material productivity.

For the BRICS countries at first a strong decrease in variation, i.e., σ-convergence, can be observed up until 2004. In the period from 2005, however, the standard deviation increased. It remains to be seen if the rise in the standard deviation since 2005 is substantial. The BRICS countries were also able to increase their mean MP more strongly than the two other groups. Thus, until 2005 the BRICS countries experienced σ-convergence within their group, and average material productivity increased constantly.

The transformation economies show a slightly different picture. Their mean increased over time, by less than the BRICS' mean, but more than the OECD was

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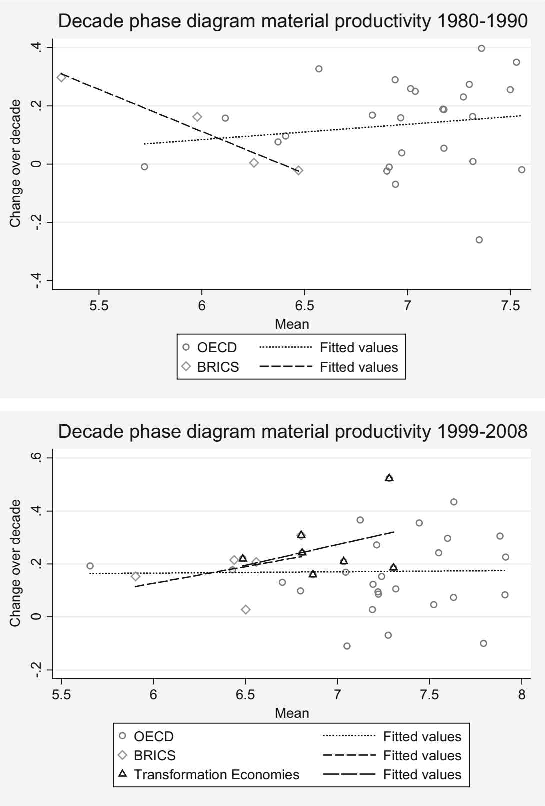
[4] Data for Estonia starts in 1995.

able to increase its mean. The standard deviation decreased in the first quinquennial starting in 1993, which implies that in this first period the variation between the different economies decreased, indicating σ-convergence. Since 1998, however, the standard deviation has increased again, indicating σ-divergence. For both the BRICS and the transformation economies, a leap in variation can be observed in the last period considered. The same is true for the OECD countries in the second last period; however, in the OECD the variation decreased sharply in the period after the increase. It remains to be seen if the same trend will occur in the BRICS and transformation economies.

Overall, it seems that while all three country groups display increasing means, this does not automatically imply that the variation in the subgroups, i.e., the standard deviation, decreases. The group with the highest mean MP also displays the highest variation in MP, while the two other groups are characterized by lower means as well as lower variation. This implies that the differences within the OECD countries are more pronounced than the differences within the two other groups. This might be due to the fact that an increasing mean of MP goes hand in hand with increasing variation or maybe that the transformation economies and the BRICS countries are more homogeneous in terms of their economic structures and therefore display less variation. A look at the development of per capita incomes among different income groups globally indicates that the variation between high-income and low-income countries does not differ as strongly (see Mayer-Foulkes 2010). Therefore, it can be concluded that the high variation in OECD material productivity is not driven by a high variation in per capita incomes, but rather by a high variation in material consumption. It remains an open question whether material productivity development in this regard differs from development patterns of per capita income per se or whether other explanations can be found. Taking a look at the different levels of the mean of material productivity, it can be seen that the three subgroups are located at very different positions of material productivity development. The BRICS economies can be found on the bottom end, the transition economies in the middle, and the OECD at the top end.

Relating the level of material productivity to the findings of σ-convergence, one may speculate that countries might follow different phases in their development: an initial phase of σ-convergent development of material productivity becomes a divergent development at a medium-high level of average material productivity until differences between the members become smaller again as average material productivity increases. The leap in variation between a medium-high level of MP and the high-level MP unfortunately remains unexplained. The reasons for this transition are unclear. One possible explanation is that as material productivity rises, differences between country groups actually become smaller. Yet this is somehow contradicted by the high level of variation in the OECD countries. It is also possible that the recent divergence that can be observed in the BRICS and transformation economies is only temporary, as it was in the OECD between 2000 and 2004. In this case the conclusion would look very different. It is therefore vital to monitor future development. It is also possible that in the case of this sample, some self-selection bias is present, because the OECD and BRICS countries are samples of economically successful countries. It can be expected that economically

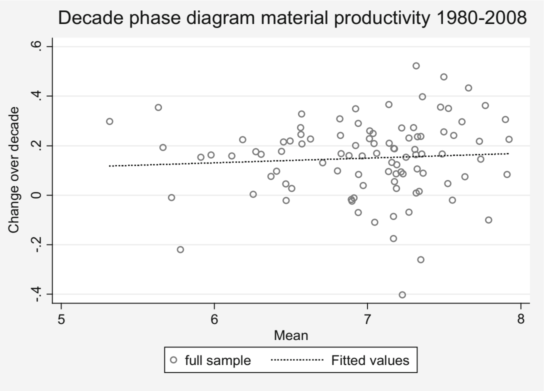
Fig. 8.10 Decade phase material productivity 1980 and 1999. *Source*: Own calculation based on Global Materialflow Database (2012)



successful countries display higher levels of productivity and these higher productivity levels may also be mirrored in higher levels of material productivity. Also, beyond certain levels of income, a higher income may motivate environmental protection which may also affect the material productivity of an economy. This is similar to the idea of an environmental Kuznets curve, which postulates an inverted-U relationship between pollution and economic development. Overall, in general the data seems to mirror a transition towards higher average material productivity and towards σ-convergence. However, there are no signs of a convergence club for two or more of the groups.

Next, decade phase diagrams were constructed in order to take a look at the mean and change of MP over time, again following Mayer-Foulkes (2010). Decade phase diagrams show the level of material productivity on the *x*-axis and the change of MP across a decade on the *y*-axis. This kind of diagram can help to inform about convergence in the sense of β-convergence, as it indicates the direction of the change rate as well as levels of material productivity. The change of material productivity is calculated as the difference between the last years in the decade, i.e., 1989 and 2008, and the first years in the decade, i.e., 1980 and 1999, respectively. As the series considered here are log series, the resulting delta can be interpreted as percentage change over the decade. In the following graphs Ireland

Fig. 8.11 Decade phase material productivity 1980–2008. *Source*: Own calculation based on Global Materialflow Database (2012)



is not included due to data availability problems. Figure 8.10 displays the development of material productivity in the decade 1980–1990 and the decade 1999–2008. For the 1980s the graph shows today's OECD countries, excluding all transformation economies but Hungary, and the BRICS countries, excluding the Russian Federation. In the graph for the decade starting 1999, all countries but the Netherlands and Ireland are included. Note that the Russian Federation is member of two subgroups, namely, the BRICS and the transformation countries.

Turning to the results of the decade phase diagrams: in the decade of 1980 within the OECD, β-divergence seems to be present. This manifests in the tendency of more productive countries to display higher growth rates of material productivity than their less productive group members within the OECD. In the BRICS countries the opposite is observable. Here, for example, the least productive country, China, displays a higher growth rate than its group members.

In the decade 1999–2008, the individual country groups display very different patterns. The OECD countries seem to display a constant change in MP of around 0.2 percentage points over the decade, irrespective of their levels of material productivity. This implies neither convergence nor divergence but rather that development froze. The BRICS and transformation economies, however, display divergence in this decade. Within these two groups the material productivity increases faster, the higher was their mean material productivity. This means that within the individual groups, there is no tendency for the less productive to catch to their more productive counterparts up.

Overall, after visually inspecting these decade phase diagrams, one might speculate that material productivity traverses different phases in its growth process. Low levels of material productivity seem to be marked by β-convergence. As productivity increases β-divergence seems to become the dominant pattern, and as material productivity increases further, a freezing of the pattern, i.e., neither convergence nor divergence, seems to occur. Consequently, when the full sample for the whole period is considered, there is a slight tendency towards divergence (see Fig. 8.11). This obviously is a result of the divergence process in the numerous OECD countries in the first decade and in the BRICS and transformation economies in the second decade starting 1999.

Summing up, the descriptive analysis of convergence and divergence patterns proposes that MP follows different transition phases: as average material productivity increases, σ-convergence can be identified at a low level of MP followed by a phase of divergent behavior as MP increases and, finally, with a phase of σ-convergence at the highest average level of MP. The analysis of this sample did not suggest the existence of a convergence club with similar developments for two or more of the groups considered. The patterns for β-convergence look a little different with first a process of convergence and then divergence at medium levels of MP, and at high levels of material productivity, a freezing of the process seems to occur.

The next chapter will examine cross-country material productivity developments over time more systematically by means of regression analysis, trying to generalize the conclusions drawn from this sample of countries.

Chapter 9
Examination of Material Productivity Convergence

This section asks specifically whether a convergence process of material productivity can be observed. The descriptive statistics have shown that development patterns differ greatly, and this section aims at examining the convergence and divergence patterns revealed by the previous analysis in a regression context. Convergence analysis is typically concerned with three different types of convergence. The examination of productivity levels in terms of the cross-sectional distribution of the variable of interest is referred to as σ-convergence analysis. β-Convergence is based on the notion that less productive countries are able to realize the *advantage of backwardness* in the sense of Gerschenkron (1962) and by realizing higher growth rates than their more productive counterparts are therefore able to catch up with them. And thirdly, time-series concepts of convergence analyze whether an assimilation in terms of levels can be observed.

In Sect. 9.1 the cross-sectional distribution of material productivity will be examined for σ-convergence between 1980 and 2008. Then, in Sect. 9.2 regression analysis is used to test for unconditional (Sects. 9.2.1 and 9.2.2) and conditional β-convergence (Sect. 9.2.3) of material productivity. Section 9.3 examines material productivity convergence by means of time-series methods, namely, panel unit root (PUR) tests.

9.1 σ-Convergence

σ-convergence asks the question whether differences between countries' material productivity diminish over time. A reduction of the material productivity differences between countries is referred to as σ-convergence. To answer this question usually one of two measures of dispersion is applied, either the standard deviation of the log of material productivity or the coefficient of variation of material productivity [e.g., see Miketa and Mulder (2005), Mulder and de Groot (2007), Dalgaard and Vastrup (2001)]. Both measures describe the dispersion of the data.

L. Talmon-Gros, *Development Patterns of Material Productivity*, Contributions to Economics, DOI 10.1007/978-3-319-02538-4_9,

The standard deviation takes the mean as the point of reference, and it is calculated as the square root of the variance:

$$s = \sqrt{\frac{1}{n}\sum (x_1 - \overline{x})^2} \tag{9.1}$$

The standard deviation is measured in the same units as the observations. It is not normalized to the mean; therefore, it is possible that a variable with a high mean also displays a higher standard deviation than a variable with a lower mean. In order to avoid this problem, the coefficient of variation can be used. The coefficient of variation (CV)

$$v = \frac{s}{\overline{x}} \tag{9.2}$$

normalizes the standard deviation. It is therefore independent of the units of measurement of the observations.

In order to avoid possible biases, both measures are calculated for the full period 1980–2008 for all countries which provided data in 1980 and, secondly, for the full country sample since 1995.[1]

In both cases the standard deviation and the coefficient of variation have increased during the period considered, as Table 9.1 shows.

For the period 1980–2008, the SD of log MP increased from 0.5498 to 0.5664 and the CV of MP increased from 0.4373 to 0.4809. A similar pattern, though not as pronounced, can be found for the period 1995–2008. Here the SD increased from 0.5181 to 0.5324 and the CV rose from 0.4646 to 0.4778. Both measures indicate the same result, namely, σ-divergence between 1980 and 2008.

Figure 9.1 shows the development of the standard deviation of material productivity graphically, also with respect to the two different time periods. In the first period (1980–2008), only Hungary is included of the transformation economies. For this period and country sample, it is very clear that until the mid-1990s a substantial decrease of the SD of log MP can be observed, i.e., σ-convergence took place. From 1995 onwards, the standard deviation of log MP increased strongly and finally even exceeded the starting SD, indicating σ-divergence. Combination of these different periods results in the finding of σ-divergence shown above. Also in the time period between 1995 and 2008 for the full sample of OECD and BRICS countries σ-divergence can be observed. During this period an increase in the standard deviation can be observed, which results in a higher SD in the year 2008 than in 1995. From Fig. 9.1 it becomes clear that the development of the dispersion of material productivity can be divided into two periods, the period before 1994 and the period afterwards.

This division seems to have little to do with the inclusion of the transformation economies in the sample under consideration, as the 1980 sample, which excluded

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[1] Ireland is excluded from this analysis due to data availability problems.

Table 9.1 Standard deviation and coefficient of variation

Year	Standard deviation (log MP)	Coefficient of variation (MP)
1980	0.5498	0.4373
2008	0.5664	0.4809
1995	0.5181	0.4646
2008	0.5324	0.4778

Source: Own calculation based on Global Materialflow Database (2012)

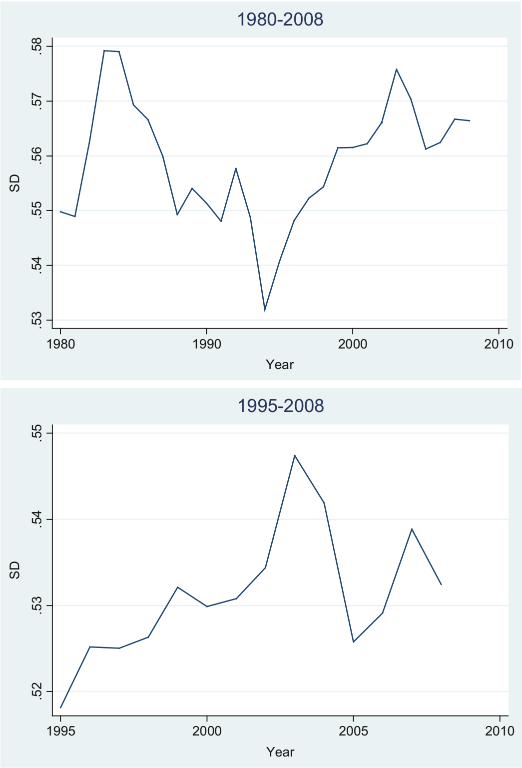

Fig. 9.1 σ-Convergence for the 1980 sample and the full sample. *Source*: Own calculation based on Global Materialflow Database (2012)

the transformation economies, also displayed relatively strong σ-divergence and the amount of divergence rather decreased with the inclusion of the transformation economies. This also implies that within the transformation economies, σ-divergence was less pronounced than in the overall sample. The results found here contradict the results found in the descriptive statistics analysis. The differences between these results can be explained by differences in calculation methods. Here, the analysis of the 1980–2008 period only includes those countries which provided data for 1980; no country data was being added in successive years. In the descriptive analysis the data was included in the generation of the graph as data became available. If Fig. 8.8 and the first part of Fig. 9.1 are compared, a similar development can be identified up until the early 1990s, when data for the transformation economies became available. Also, it has to be noted that Figs. 8.8 and 8.9 are drawn on the basis of 5-year averages of standard deviations and Fig. 9.1 is based on yearly values. The successive inclusion of the transformation economies in the graphs of the descriptive analysis leads to a lower overall standard deviation, because, as noted before, the mean of the transformation economies is closer to the mean of the OECD so that a reduction of the SD then occurs automatically. As the transformation economies are not included in the graph for σ-convergence, this effect does not occur; instead it appears that the differences between the countries of the 1980 sample become more pronounced over time. The same pattern can be found in the graph for the full country sample since 1995: the differences increase over time, both graphs showing that tendency. The differences in magnitude are again a result of the different approaches.[2]

In conclusion, while σ-divergence can be observed in both time periods and for both country samples considered, the intensity of divergence seems to be less pronounced when the transformation economies are included in the sample. Moreover, two different regimes of material productivity development seem to be identifiable over the almost three decades examined here: a process of σ-convergence until 1994 is followed by a rapid increase in the standard deviation of log MP, i.e., σ-divergence, since then. Possible explanations for this development may be there was no β-convergence between 1994 and 2008, which could facilitate σ-convergence, or that either of the two components of material productivity, GDP or DMC, or both, followed a divergent development path which then led the indicator MP to diverge also.

Besides the question of whether cross-country differences decrease over time, the second essential question that convergence analysis poses is whether less productive countries are able to catch up with more productive ones, i.e., are able to realize higher growth rates than their counterpart, commonly known as β-convergence. The next section will examine if the findings of β-convergence and β-divergence identified in the descriptive analysis can be confirmed in a regression analysis.

9.2 Regression Analysis of β-Convergence

The analysis of the previous section showed that material productivity displays mixed patterns of σ-convergence and divergence over time. Sala-i-Martin (1996) shows that β-convergence is a necessary but not sufficient condition for σ-convergence. Therefore, in this section the patterns that MP displays in terms of β-convergence will be analyzed as well as how these results relate to the above findings of σ-convergence and σ-divergence.

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[2] Moreover, Ireland was excluded from the analysis.

As mentioned before, one can distinguish between two forms of β-convergence, *absolute or unconditional* convergence and *relative or conditional convergence*. As applied to material productivity, unconditional convergence assumes that material productivity will converge to a uniform level for all countries, whereas conditional convergence allows different levels of material productivity for different countries depending on country-specific characteristics. Technically, three different approaches were chosen in this dissertation to examine β-convergence: starting in a cross-sectional framework, unconditional β-convergence is examined using the method used by Mankiw et al. (1992).

Secondly, as the dataset available has a panel structure, both unconditional and conditional convergence are examined in a panel data context [see Islam (1995)]. Finally, time-series forecast convergence is tested by means of different PUR tests, a method proposed by Evans (1998).

9.2.1 Cross-Sectional Analysis of Unconditional β-Convergence

Unconditional β-convergence of material productivity in a cross-sectional context is examined by regressing the change of the log of MP over the period 1980–2008 on the log of MP in 1980 [see, e.g., Mankiw et al. (1992)]. The cross-country regression

$$g_{it} = \alpha + \beta_i \log(\mathrm{MP})_{i,t-1} + \varepsilon_{it} \tag{9.3}$$

is estimated. The growth rate of material productivity g_{it} is regressed on the initial level of material productivity $\beta_i \log(\mathrm{MP})_{i,t-1}$ and a constant α and an error term ε_{it} is included. The country sample is restricted by incomplete data availability for 1980; therefore, the Czech Republic, Estonia, Poland, the Slovak Republic, Slovenia, Russia, and Ireland are not included in this analysis. Table 9.2 shows the results of the relation between the change of material productivity in 1980–2008 and the starting level of MP in 1980.

For the overall sample, the explanatory value of model is quite low with a value of 0.05 for R^2 and 0.02, i.e., <5 % of the variance of the growth rate of MP is explained by the starting level of MP. The p-value of the model, indicating whether all the coefficients in the model are different from zero, is also above typical significance levels. Thus, the model quality is low. Even though the coefficient of the starting value of MP is negative, which would indicate convergence, the corresponding t-values and p-values are not significant at typical significance levels. Consequently, as model quality and coefficient significance are low, no conclusion with regard to the relation between material productivity growth and its initial level can be drawn.

Table 9.2 Regression results unconditional convergence (cross section)

Sample	Coefficient	t	$P > \lvert t \rvert$	R^2	Prob $> F$
Overall sample	−0.130	−1.24	0.224	0.052	0.224
OECD	−0.105	−0.72	0.476	0.021	0.476
BICS	−0.564*	−3.32	0.080	0.847	0.080
Transformation economies 1994–2008	−0.0403	−0.27	0.799	0.018	0.799
Overall sample 1980–1994	−0.113	−1.55	0.133	0.079	0.133
BICS 1980–1994	−0.345**	−6.63	0.022	0.957	0.022
OECD 1980–1994	−0.138	−1.33	0.195	0.069	0.195

Source: Own calculation based on Global Materialflow Database (2012)
Note: *significant at a 10 % significance level, **significant at a 5 % significance level, ***significant at a 1 % significance level

When the OECD and BICS countries are considered separately, two different patterns become visible. No statistical relationship can be determined for initial MP and the growth of MP in the OECD countries.

The model for Brazil, India, China, and South Africa has good explanatory value, and the coefficient indicates unconditional β-convergence at the 10 % significance level. The size of the coefficient (−0.345) is considerably higher than the values for unconditional income convergence found, for example, by Barro and Sala-i-Martin (1992). However, they are more or less in line with the values for unconditional income convergence of non-oil states identified by Mankiw et al. (1992).

Data for all transformation economies is available since 1994. Therefore, the convergence analysis for these economies can only be conducted between 1994 and 2008. It indicated no clear relationship between initial MP and subsequent MP growth. The model quality is low, and the coefficient of initial MP is negative but is not statistically significant.

Earlier, the analysis of σ-convergence revealed that the period from 1980 to 2008 could be divided up into two regimes, the first from 1980 to 1994 in which σ-convergence took place and a second phase from 1995 to 2008, in which σ-divergence took place. Next, the question if β-convergence between 1980 and 1994 contributed to the process of σ-convergence during the same period was examined. Regression analysis of time period between 1980 and 1994 shows that for the full sample, the coefficient of initial MP is negative between 1980 and 1994, thus indicating convergence. However, the p-value of both the model and the coefficient is above the 10 % significance level. It can therefore not be confidently concluded that unconditional β-convergence was present between 1980 and 1994.

Analysis of the OECD and BICS countries separately between 1980 and 1994 showed that in this sub-period the BICS countries experienced unconditional β-convergence. For the OECD countries the coefficient of initial MP is negative; however, it is not statistically significant at the 10 % level or better also the overall model quality is low. Therefore, it cannot be concluded that the OECD countries experienced unconditional β-convergence in the period between 1980 and 1994.

All in all, the analysis revealed that unconditional β-convergence can only be observed for the BICS countries both for the full period 1980–2008 and between 1980 and 1994. It is possible that this β-convergence contributed at least to some extent to the σ-convergence process observed for the full sample between 1980 and 1994.

However, the cross-sectional approach is subject to severe shortcomings including the argument discussed earlier that one data point per country is a very weak basis for making an estimation. In order to overcome these shortcomings, a panel data approach was chosen and unconditional β-convergence was examined again.

9.2.2 Panel Analysis of Unconditional β-Convergence

For the panel setup the approach is quite similar to the cross-sectional analysis and follows Miketa and Mulder (2005). Again, the average growth rate (g) of material productivity is regressed on the initial level of MP (log MP) according to

$$g_{it} = \alpha + \beta \log(\mathrm{MP})_{i,t-1} + \eta_t + \varepsilon_{it} \tag{9.4}$$

Here i denotes the individual countries, t denotes the time, η_t is a period-specific fixed effect, and ε_{it} the error term. Practically, the period-specific fixed effect is included through the introduction of time dummies. The major difference from the cross-sectional approach is that the total period is divided into five sub-periods of 5 years and one sub-period 4 years long (2005–2008). Using 5-year intervals instead of yearly intervals has the effect that the error term is less influenced by business cycle fluctuations and serial correlation, as Islam (1995) argues. This implies that the average growth rates of the regression Eq. (9.4) are 5-year averages and one 4-year average and the initial level of MP is always the first MP value of each of the 5-year intervals and the 4-year interval, respectively.

The results of this analysis, which can be found in Table 9.3, confirm the results from the cross-sectional framework.

For the overall sample of countries, again the model quality is sufficient at a 5 % significance level or higher.[3] The coefficient of the initial MP is positive, which indicates that more productive countries are able to grow faster, i.e., divergence is present. The coefficient is also statistically significant. For the BRICS countries and the transformation economies, the model quality is low and the coefficients are not statistically significant. If the OECD countries are considered separately, these results are altered. The model quality is acceptable at a 5 % significance level, and the coefficient is positive and also statistically significant. This implies that the OECD countries, just like the overall sample, displayed β-divergence in the period

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[3] The R^2 is omitted for the fixed-effects estimations, as in this context they are not considered reliable.

Table 9.3 Regression results unconditional β-convergence (panel)

Sample	Coefficient	t	$P > \|t\|$	Prob $> F$
Overall sample	0.116**	2.48	0.014	0.014
OECD	0.135**	2.54	0.012	0.012
BRICS	0.013	0.16	0.871	0.871
Transformation economies	0.402	1.60	0.129	0.129

Source: Own calculation based on Global Materialflow Database (2012)

Note:*significant at a 10 % significance level, **significant at a 5 % significance level, ***significant at a 1 % significance level

between 1980 and 2008, i.e., more productive countries improved their productivity faster than less productive countries.

With regard to unconditional β-convergence, the following can be recorded: generally, for the full sample no unconditional β-convergence can be observed. However, if the BICS countries are analyzed separately from 1980 to 1995 in a cross-sectional framework, unconditional β-convergence can be identified. Also if the OECD countries are considered in a panel framework, β-divergence can be observed in the period 1980–2008 within the OECD countries. Overall, however, it can be concluded that the analysis of unconditional β-convergence for the full sample provided no statistically significant results. Generally, the fact that only a single explanatory variable was included suggests that the explanatory value of the models is generally rather low. Possibly other factors than the catch-up mechanism determine the differences in MP growth performance. These factors might be country specific and/or time specific. Therefore, in the next section, fixed effects will be included in order to test for conditional β-convergence.

9.2.3 Panel Analysis of Conditional β-Convergence

Conditional convergence implies that all countries converge to different growth paths of material productivity and do not converge towards one uniform path. It is therefore possible that considerable cross-country differences persist because the determinants of material productivity development differ between countries. These country-specific factors are included in the regression equation instead of the common intercept as follows:

$$g_{it} = \beta \log(\mathrm{MP})_{i,t-1} + \eta_t + \mu_i + \varepsilon_{it} \tag{9.5}$$

Again i denotes the individual countries, t denotes the time, η_t is a period-specific fixed effect, μ_{it} is an country-specific fixed effect, and ε_{it} is the error term. The entity-specific fixed effect subsumes all kinds of country-specific factors that affect material productivity and that are not included as explanatory variables. These factors have been part of the error term in Eq. (9.4).

Table 9.4 Regression results conditional β-convergence

Sample	Coefficient	t	$P > \|t\|$	Prob $> F$
Overall sample	0.294***	3.49	0.001	0.012
OECD	0.319	3.47	0.002	0.037
BRICS	−0.0293	−0.19	0.849	0.212
Transformation economies	1.356	13.79	0.000	.

Source: Own calculation based on Global Materialflow Database (2012)
Note: *significant at a 10 % significance level, **significant at a 5 % significance level, ***significant at a 1 % significance level

The results of the fixed-effects regression indicate the following (see Table 9.4): for the full country sample, the p-value for the model is within the 5 % significance level (0.012), the coefficient of log of initial MP is positive (0.2939) and significant at the 1 % level (0.001), and this indicates β-divergence for the full sample.

The OECD countries display the same pattern of β-divergence. Specifically, the p-value of the model again lies within the 5 % significance level (0.037) indicating that the model fit is acceptable. The coefficient is positive (0.319) and statistically significant (0.002), and this suggests that an increase of initial MP will lead to an increase in growth of material productivity, thus divergence.

For the BRICS countries, the model proves not to be reliable with a p-value of 0.2116. However, the coefficient of log MP is negative (−0.0293), indicating convergence, but statistically it is not significant (p-value 0.849).

The model for the transformation economies is burdened with uncertainty, presumably due to the small amount of data points available for this subsample. The coefficient is in comparison strongly positive (1.2364) and statistically significant (0.00). To what extent this is a reliable estimate is difficult to assess. It would, however, also indicate divergence.[4]

Summing up, the examination of conditional β-convergence reveals that no statistically significant patterns of conditional β-convergence can be identified. On the contrary, the statistically significant results indicate β-divergence, rather than convergence. Shortcomings of the panel approach have been discussed earlier, and it is possible that in this analysis problems have arisen due to the small sample size and the short frequency of the data. To overcome the limitations of cross-sectional and panel analysis, time-series approaches have been chosen to examine

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[4] In contrast to other examinations, for instance, the analysis of energy productivity convergence by Miketa and Mulder (2005) or the analysis of factors influencing material use by van der Voet et al. (2005), in this dissertation no control variables besides the fixed effects are introduced in the estimation of conditional convergence. This is due to several reasons: Firstly, there is no agreed-upon set of (policy) variables considered to be relevant for material use and material productivity. Secondly, in panels consisting of several economies like the one examined here, variables may display autocorrelation and non-stationarity. Consequently, cointegration and panel unit root approaches are necessary to obtain valid inference on explanatory variables. Due to time and space constraints as well as the lack of a commonly accepted theory on possible influencing factors, no such analysis was conducted. Instead, the non-stationarity of the data is taken into account in the convergence analysis by examining convergence by means of panel unit root tests.

convergence, for instance, in Bernard and Durlauf (1995), Bernard and Durlauf (1996), Evans and Karras (1996), and Evans (1998). Moreover, the analysis of growth rates alone does not provide sufficient information with regard to a possible reduction of material consumption levels. Therefore, in the next section PUR tests are applied to test for convergence of material productivity in terms of levels.

9.3 Testing for Convergence with Panel Unit Root Tests

In this section the results from the PUR tests will be presented and discussed. First the whole panel and its different subsamples are examined for time-series forecast convergence by means of PUR tests. Next, different subsamples constructed on the basis of theoretical insights are examined separately in order to investigate the possible existence of convergence clubs.

9.3.1 Time-Series Forecast Convergence

Originally, convergence of per capita output in a time-series environment is understood to occur if the output forecasts converge as the forecasting horizon increases (Bernard and Durlauf 1996). In Sect. 4.2.3 it was shown that convergence can be tested by conducting Dickey-Fuller regressions on a first-order autoregressive process. The model to be analyzed is the following:

$$\Delta(y_{nt}) = \rho\, y_{n,t-i} + z_{it}^{'} \gamma_{it} + \varepsilon_{it} \tag{9.6}$$

where $i = 1,\ldots,N$ indexes panel members, $t = 1,\ldots,T$ indexes time, ε_{it} is the stationary error term, and y_{nt} is the variable under consideration. This is simply another way of writing Eq. (4.79) and excluding the higher order serial correlation. In Stata the z_{it} term by default is set to equal to 1 and then represent the panel-specific means (fixed effects). It can also be specified to contain panel-specific means and a time trend, or it can be excluded if wished (see StataCorp 2009). The unit root null hypothesis on PUR test $H_0 : \rho_i = 0$ can in this setup be interpreted as the null of non-convergence (Pedroni and Yao 2006). Failure to reject the null hypothesis thus implies divergence. In order to analyze the patterns of MP convergence, the Im et al (2003) and the Fisher-type PUR tests (Maddala and Wu 1999 and Choi 2001) are conducted in turn.

As in Evans (1998) and Pedroni and Yao (2006), it is supposed that y_{nt} is difference stationary, thus exhibits unit root behavior individually. Pretesting of the data at hand indicated that this assumption is valid for this data. The results of the ADF on the log MP of the individual countries as well as on the first differences of log MP can be found in the appendix.

Before the analysis is conducted, the following details on the technical implementation should be noted: all three tests are included in the statistical software Stata® release 11. The software allows specification of options for the different tests [see StataCorp (2009)]. The option *trend* includes a linear time trend, and the option *demean* subtracts cross-sectional means for each time period, i.e., introduces fixed effects, can be specified for both tests. Demeaning is a procedure for mitigating the cross-sectional dependence suggested by Levin et al. (2002).

The Fisher-type tests demand the specification of whether the ADF unit root tests or the Phillips-Perron unit root tests are to be used. Here, only the ADF unit root tests are used. Moreover, the number of lags, removing the higher order autoregressive components of the series, has to be specified. The Fisher-type tests assume that data is generated by an AR(1) process, and higher order processes can be catered for by including a higher number of lags. Any option allowed by the unit root test commands *dfuller* or *pperon* can be included, for instance, a drift can be included.

The IPS test allows the specification of the lag structure for the ADF regression either as a nonnegative integer or based on information criteria like the Akaike information criterion (AIC) which can be used to determine the lag length for which the AIC is minimized. For this the maximum lag length has to be specified. This selection procedure based on the AIC is done for each panel separately, so that each panel may use different ADF regressions with a different number of lags.

The lag length selection is an important aspect of PUR tests, and both individual and PUR tests are known to be sensitive with regard to the number of lags *(k)* fitted. Usually, the lag length in ADF tests is determined by a data-dependent step-down procedure, typically used in the ADF unit root tests in conventional time-series regressions (Pedroni and Yao 2006). The procedure starts with choosing a sufficiently large number of lags and then step-by-step reduction of the order of lags until the test becomes significant. Pedroni and Yao recommend 1/5 of the sample length, rounded to the nearest integer as starting value. In conventional time-series analysis, Schwert (1989) recommends using

$$k_{\max} = \operatorname{int}\left\{12(n/100)^{25}\right\} \tag{9.7}$$

rounding down to the nearest integer [see Hackl (2005, p. 243)]. Pedroni and Yao's approach yields larger numbers, and in order to ensure that the correct number of lags is chosen, their initial value is used as the starting value.

The critical values for the Fisher-type test are given by the χ^2 distribution with $2N$ degrees of freedom. Next, the results of the panel as a whole and the different subgroups will be presented and discussed.

First, the full panel and the subgroups OECD, BRICS, and transformation economies were examined. Varying lag lengths were tested as well as specifications with and without a linear trend included as well as with and without demeaning of the variable. Table 9.5 displays the results of the PUR tests for the full sample and the transformation economies. Only statistically significant results are reported.

Table 9.5 PUR tests' results

Sample considered	Type	Type of test statistic	Value of test statistic	*p*-value	*N*	Specification
Full sample	Fisher	χ^2	157.923	0.0000	37	dfuller demean trend lags(3)
Full sample	IPS	$W_{\text{t-bar}}$	−4.815	0.0000	37	demean trend lags (aic 3)
Transformation economies	Fisher	χ^2	65.09	0.0000	7	dfuller demean trend lags(3)
Transformation economies	IPS	$W_{\text{t-bar}}$	−4.014	0.0000	7	demean trend lags (aic 3)

Source: Own calculation based on Global Materialflow Database (2012)

The analysis of the OECD and BRICS countries separately did not yield statistically significant results; therefore, they are not included in the table. However, failure to reject the unit root null can in this setup be interpreted as presence of divergence for the OECD and BRICS countries. Several different specifications of the PUR tests were tried. Next, the results for the full country sample and the transformation economies will be discussed in greater detail next.

Taking a look at the results for the full sample first, the χ^2 statistic of the Fisher test displays a value of 157.92. It thus strongly rejects the null hypothesis (H0) that all panels contain unit roots in favor of the alternative that some panels are stationary. One can conclude that at least one pair of countries converges to one another. The IPS test statistic also rejects its H0 that all countries diverge in favor of the alternative that some countries are converging.

In order to explore whether the results of the Fisher-type and IPS tests are driven by a few extreme values rather than an overall tendency, the overall result can be broken down into the results of the unit root tests of the individual countries. As this feature is not part of the xtunitroot command implemented in Stata, the user written predecessor of xtunitroot the xtfisher command by Scott Merryman was used (Merryman 2004). As the xtfisher command does not include the option demean, the data were first demeaned "manually" before the test was conducted. In order to ensure that no errors were made in the process of demeaning, the results of xtunitroot fisher and xtfisher were compared, and only very minor differences due to rounding were found to be present.

Table 9.6 displays the test results for the individual countries' unit root test in the full sample, and the value of their ADF test statistic and the corresponding *p*-values are given. The countries printed in italic represent the countries which individually rejected the H0 of non-stationarity at a 10 % level or better. The overall test, however, rejects the null at a higher level of significance. At first sight, it seems that these few countries drive the overall result. Following Pedroni and Yao's (2006) elaborations on this topic, the overall rejection of the H0 despite the fact that not all or in this case not even a majority of the countries individually reject the hull hypothesis is a result of the fact that although the signals from each country are weak, the values of the test statistics generally lie on the left side of the distribution,

Table 9.6 Full sample: individual unit root test results

ID	Country	Z(*t*)	*p*-value	ID	Country	Z(*t*)	*p*-value
1	Australia	−2.150	0.5183	20	Mexico	−2.758	0.2129
2	Austria	−2.569	0.2942	21	Netherlands	NA	NA
3	Belgium-Luxembourg	−1.892	0.6590	22	New Zealand	−1.091	0.9306
4	Canada	−0.180	0.9919	23	Norway	−0.616	0.9781
5	*Chile*	*−3.173*	*0.0899*	*24*	*Poland*	*−5.648*	*0.0000*
6	Czech Republic	−0.488	0.9839	*25*	*Portugal*	*−4.526*	*0.0014*
7	Denmark	−2.414	0.3721	*26*	*Slovak Republic*	*−9.877*	*0.0000*
8	*Estonia*	*−3.255*	*0.0740*	27	Slovenia	0.123	0.9953
9	Finland	−1.258	0.8979	28	Spain	−1.588	0.7969
10	France	−0.179	0.9919	29	Sweden	−0.203	0.9915
11	Germany	−1.989	0.6075	30	Switzerland	−2.068	0.5639
12	Greece	−1.585	0.7982	*31*	*Turkey*	*−3.432*	*0.0472*
13	Hungary	−2.641	0.2613	32	UK	−2.568	0.2948
14	Iceland	−1.215	0.9074	33	USA	−1.442	0.8482
15	Ireland	NA	NA	34	Brazil	−1.829	0.6908
16	Israel	−1.625	0.7827	*35*	*Russian Federation*	*−3.349*	*0.0586*
17	Italy	−2.041	0.5789	*36*	*India*	*−3.799*	*0.0166*
18	Japan	−1.918	0.6453	38	China	−2.273	0.4490
19	Korea	−0.897	0.9565	39	South Africa	−2.445	0.3559

Source: Own calculation based on Global Materialflow Database (2012)

thus favoring rejection over non-rejection of the hypothesis. Many countries did not provide small enough *p*-values to support a rejection of the H0. However, there are a handful of countries which support rejection of the H0 on a significance level at 35 % or better.[5] Individually, they cannot be considered as sufficient evidence. The combination of the evidence of these marginally supportive countries, however, suffices to generate a signal strong enough to allow rejection of the null for the panel as a whole with greater confidence. This is how the Fisher and IPS tests work. They combine the evidence of the *p*-value and the *t*-statistic of the individual unit root tests, respectively, in order to allow conclusions to be drawn for the panel as a whole. It can also be seen that a few of the countries lie on the very right side of the distribution with very high *p*-values, while on the other hand there are three countries lying on the extreme left of the distribution, with *p*-values of close to zero. It seems, however, that overall the combination of the signals tends towards rejection of the null hypothesis. Therefore, it can be concluded that at least a significant subset of the countries in the full sample converge towards each other.

The PUR tests for the transformation economies as a separate country sample also indicate that at least some of the transformation economies are converging. This is mirrored in the results of the Fisher and IPS tests, which strongly reject the H0 of non-convergence. Considering the individual ADF test results again,

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[5] This value of a 35 % significance level used by Pedroni and Yao will also serve as benchmark here.

Table 9.7 Transformation economies: individual unit root test results

ID	Country	Z(*t*)	*p*-value
6	Czech Republic	−1.103	0.9286
8	*Estonia*	*−3.444*	*0.0457*
13	Hungary	−1.805	0.7022
24	Poland	−2.909	0.1594
26	*Slovak Republic*	*−7.250*	*0.0000*
27	Slovenia	−1.140	0.9229
35	*Russian Federation*	*−4.815*	*0.0004*

Source: Own calculation based on Global Materialflow Database (2012)

Table 9.7 shows that the conclusion of convergence of a sizable subset of countries is not based on a single strong value but that three out of seven countries reject the H0 strongly and another country does so on a 35 % level or better.

The results reported here for the full sample and the transformation economies show that the PUR tests that were used tended in the same direction and were all highly significant. This indicates that the findings of convergence for the full sample and the transformation economies can be expected to be robust. The results of the individual unit root tests support the previous results of convergence but also provoke the question whether the pattern that can be observed might be the result of clubs of countries displaying convergence patterns. Therefore, in the next section several subsets of the data are examined for convergence club.

9.3.2 Convergence Club

This section considers the question whether groups of countries exist which form clubs with a similar development pattern of material productivity, in other words convergence clubs. In order to shed light on possible convergence clubs, separate subgroups of the panel are examined. Three different approaches were chosen to divide the panel into separate subgroups, additionally to the division into OECD, BRICS, and transformation economies earlier.

Firstly, the visual inspection of the data suggested that certain groups of countries might share similar material productivity development patterns. These considerations are the basis for the first grouping criterion. Gerschenkron's hypothesis of an advantage of backwardness was used as a second grouping criterion. A convergence-club analysis based on the initial level of material productivity in 1980 might yield interesting results with regard to whether countries with similar starting positions display similar development patterns. Finally, the role that the change in the structure of economies may play for determining clubs is examined. Each of these subdivisions will be discussed in more detail in the following.

9.3.2.1 Correlation and Growth Rates

Material productivity and DMC and GDP development between 1980 and 2008 are depicted in Fig. 9.2. An index is constructed and the year 1980 (1995 for the transformation economies) is set as base years so that a comparison of the different countries becomes possible. The figure contains two parts: the first part shows the countries with higher MP growth, and the second consists of the countries with lower MP growth. Visual inspection of the individual country graphs suggests that countries in which GDP and DMC are synchronized might display a lower growth of material productivity. On the other hand, countries in which GDP and DMC seem to display a low correlation also seem to realize higher growth rates of MP. From this observation two questions arise: Is the level of coupling of GDP and DMC actually linked with the level of MP growth? And do the countries for which decoupling is linked with higher MP growth form a convergence club?

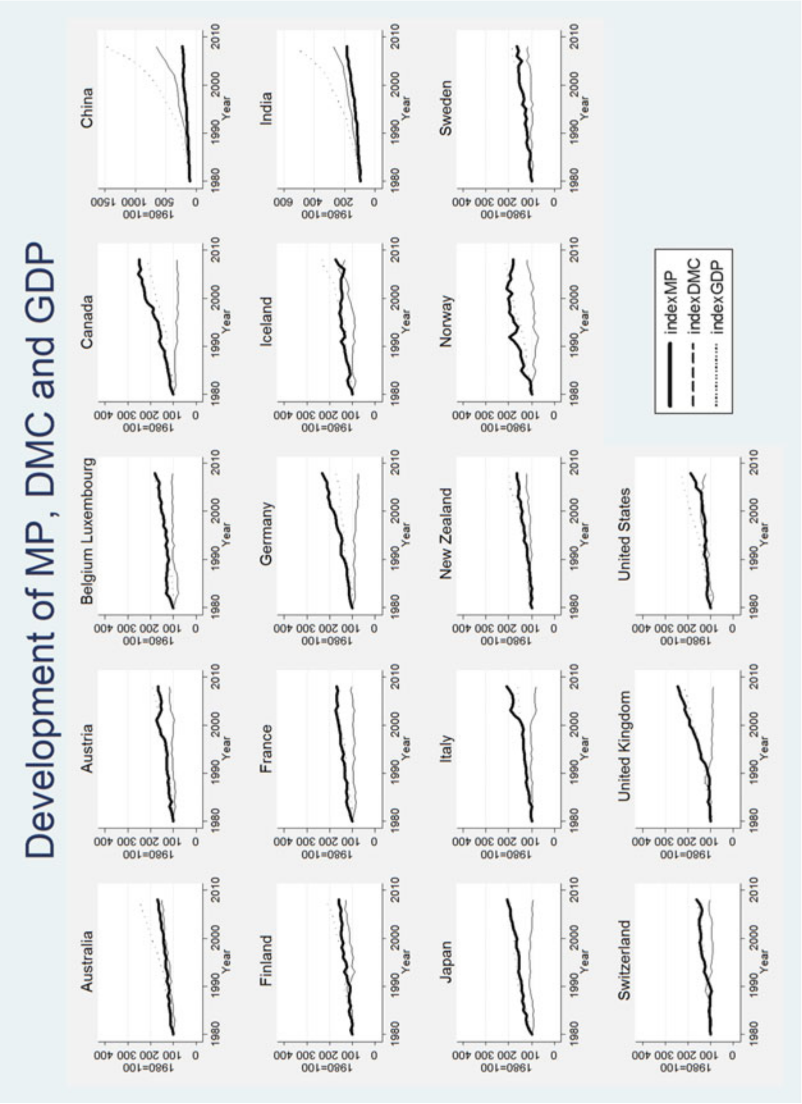
In order to examine this, the countries were first divided into terciles depending on their correlation between GDP and DMC, dividing the ordered values into three parts, each of which has the same size and contains one third of the population. Second, in order to determine how this relates to the MP growth performance, the countries were ranked according to their MP growth and again divided into terciles. Next, the information from these two tables was combined to identify a possible club determined by the decoupling performance.

Table 9.8 displays the correlation between GDP and DMC in absolute values. The data was divided into terciles to distinguish groups of countries with high correlation from those with medium and low correlation. In the first terciles the countries with a low correlation can be found, in the second those with a medium, and in the third tercile, the countries with a high correlation between GDP and DMC are presented.

Table 9.9 exhibits the overall growth of material productivity between 1980 and 2008. It is again divided into terciles with the first tercile consisting of the countries with the low growth over that period. Due to missing data, the Czech Republic, Estonia, Poland, the Russian Federation, the Slovak Republic, Slovenia, and Ireland were not included in this analysis; thus, the sample is restricted to 30 countries. The second tercile is relatively larger than the first and the third tercile, to the fact that to generate terciles the population is divided into three parts of equal value, not into three parts of the same size. The median of overall MP growth equals 0.5725, and the median correlation between GDP and DMC equals 0.8354.

Combining the information from these two tables yields that Australia, Brazil, Chile, Greece, Iceland, Israel, Korea, Mexico, Portugal, Spain, and Turkey are below the median of overall growth as well as above the median with regard to correlation between GDP and DMC. Thus, for those countries a lower level of material productivity growth is linked with a higher correlation between GDP and DMC. They form the group with high GDP–DMC correlation and low MP growth.

Conversely, a group with MP growth above the median and GDP–DMC correlation below the median can be found. This group consists of Belgium-


Development of MP, DMC and GDP
Australia
Austria
Belgium Luxembourg
Canada
China
Finland
France
Germany
Iceland
India
Japan
Italy
New Zealand
Norway
Sweden
Switzerland
United Kingdom
United States
1980=100
0 100 200 300 400
0 500 1000 1500
0 200 400 600
1980 1990 2000 2010
Year
indexMP
indexDMC
indexGDP

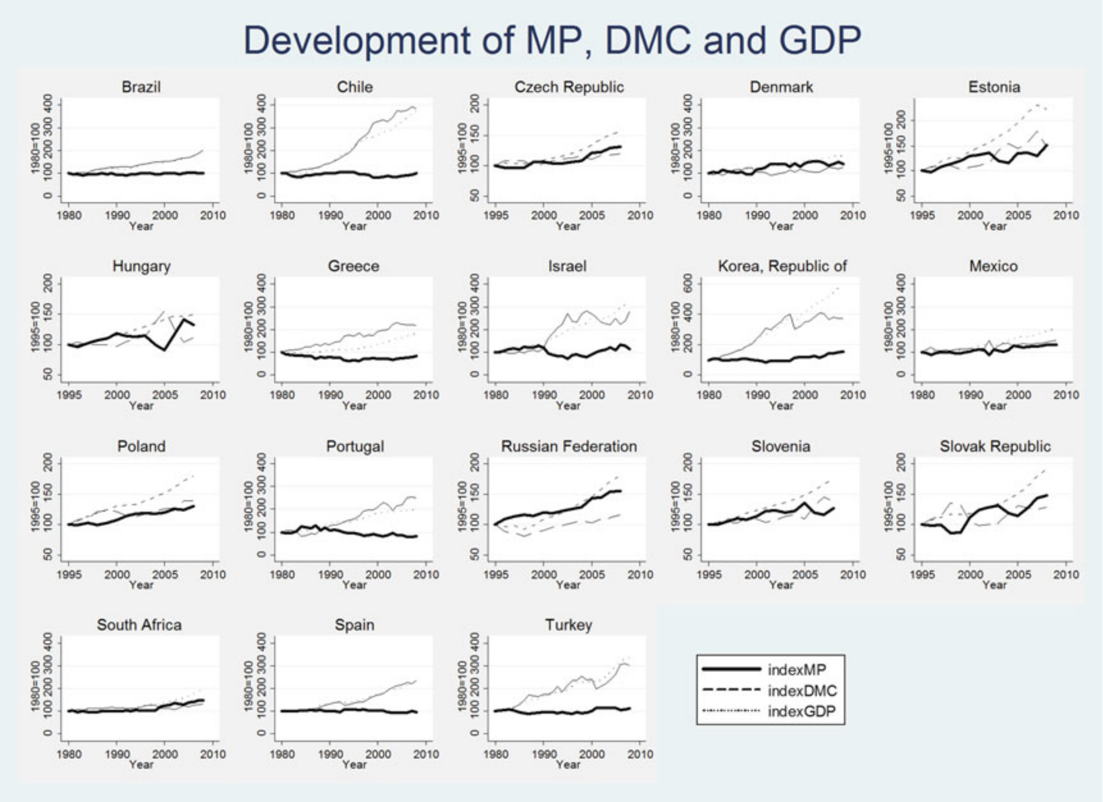


Fig. 9.2 Development of MP, DMC, and GDP. *Source*: Own calculation based on Global Materialflow Database (2012). Excluded: Ireland

Table 9.8 Correlation between GDP and DMC

Country	Correlation between GDP and DMC (absolute)	Tercile	Country	Correlation between GDP and DMC (absolute)	Tercile	Country	Correlation between GDP and DMC (absolute)	Tercile
Switzerland	0.0313358	1	Belgium-Luxembourg	0.7579541	2	Korea, Republic of	0.9196707	3
Hungary	0.3320946	1	New Zealand	0.7882526	2	Estonia	0.9280995	3
Japan	0.4127605	1	Austria	0.790207	2	Slovenia	0.9287921	3
Denmark	0.5464531	1	Finland	0.8066813	2	Turkey	0.9626486	3
Slovak Republic	0.5586734	1	Czech Republic	0.8314449	2	Portugal	0.9732915	3
Norway	0.5602718	1	Germany	0.835373	2	Ireland	0.9767069	3
Italy	0.5709467	1	USA	0.854595	2	Australia	0.9823124	3
Russian Federation	0.5817125	1	Mexico	0.872251	2	Chile	0.9841869	3
UK	0.6047689	1	Israel	0.8749565	2	Spain	0.9912021	3
France	0.6278729	1	Poland	0.8851844	2	India	0.9938268	3
Canada	0.7058934	1	Iceland	0.8853151	2	Brazil	0.9945917	3
Sweden	0.722631	1	Greece	0.9195336	2	China	0.9957097	3
South Africa	0.7440039	1						

Source: Own calculation based on Global Materialflow Database (2012)

Table 9.9 Overall growth of MP between 1980 and 2008

Country	Overall growth	Tercile	Country	Overall growth	Tercile	Country	Overall growth	Tercile
Portugal	−0.2152681	1	Korea, Republic of	0.4439273	2	Japan	0.7335567	3
Greece	−0.1982913	1	Switzerland	0.4695721	2	Italy	0.7381001	3
Spain	−0.0407209	1	Finland	0.4701605	2	China	0.8285766	3
Chile	−0.0195374	1	Sweden	0.4822264	2	Germany	0.8479037	3
Brazil	−0.007247	1	New Zealand	0.4832115	2	UK	0.8872375	3
Turkey	0.106895	1	Austria	0.5071263	2	Canada	0.9172592	3
Israel	0.1425476	1	France	0.5206065	2			
Mexico	0.2812905	1	Australia	0.5350161	2			
Denmark	0.3465247	1	Iceland	0.5543561	2			
South Africa	0.3815908	1	Hungary	0.5835962	2			
			Norway	0.5855298	2			
			Belgium-Luxembourg	0.5984368	2			
			India	0.6261511	2			
			USA	0.6265445	2			

Source: Own calculation based on Global Materialflow Database (2012)

Note: Missing—Czech Republic, Estonia, Slovak Republic, Slovenia, Poland, Russian Federation, Ireland

Table 9.10 Correlation: growth samples

Sample	Country names
High correlation GDP–DMC, low MP growth (high-low)	Australia, Brazil, Chile, Greece, Iceland, Israel, Korea, Mexico, Portugal, Spain, and Turkey
Low correlation GDP–DMC, high MP growth (low-high)	Belgium-Luxembourg, Canada, Germany, Hungary, Italy, Japan, Norway, and the UK

Source: Own calculation based on Global Materialflow Database (2012)

Luxembourg, Canada, Germany, Hungary, Italy, Japan, Norway, and the UK. The subsamples consisting of the countries with a high correlation between GDP and DMC and low MP growth and the countries with a low correlation between GDP and DMC and high MP growth can be found in Table 9.10.

The PUR tests for the subsample with a high correlation between GDP and DMC and low MP growth (high-low subsample) are displayed in Table 9.11. This table and comprises the results of all significant convergence-club results. They indicate that this subsample is converging. The Fisher and the IPS tests both reject their H0, indicating that at least a subset of the sample under consideration is converging. The test statistics are however only significant at the 10 % significance level (indicated by the italics in the table). A look at the individual unit root test results in Table 9.12 shows that only 3 out of 11 countries display a test statistic significant at the 5 % level and there is only one more country with significance values below 35 % and one slightly above. Therefore, the conclusion that a sizable subset of the countries is converging is more tentative, and this is also indicated by the lower significance level of the overall test.

Summing up, it seems that a subgroup comprising of Australia, Brazil, Chile, Greece, Iceland, Israel, Korea, Mexico, Portugal, Spain, and Turkey can be expected to converge to a common level of MP even though the evidence is not as convincing as in previous cases.

The subsample with low GDP–DMC correlation and high MP growth also displays convergence. The Fisher and IPS tests are significant at the 5 % significance level or better; see Table 9.11. With three out of eight test statistics below the 10 % significance level and another two below the 35 % level or better, the conclusion of a sizable subset of countries converging seems appropriate. Table 9.13 displays the individual unit root test results for the low-high sample.

It can therefore be concluded that a sizable subgroup of the countries in the group consisting of Belgium-Luxembourg, Canada, Germany, Hungary, Italy, Japan, Norway, and the UK is also converging.

9.3.2.2 Level of Material Productivity in 1980

Secondly, the starting level of material productivity was used as a possible determinant for the emergence of convergence clubs. Following Gerschenkron's (1962) idea of the "advantage of backwardness," this subdivision is based on the hypothesis that less productive countries might be able to grow faster, i.e., catch up with the more productive countries. This might imply that they form a convergence club.

Table 9.11 Subgroups PUR tests' results

Sample considered	Type	Type of T-stat	Value of T-stat	*p*-value	Number of panels	Specification	Excludes
High correlation— low growth	Fisher	χ^2	*31.851*	*0.0800*	11	dfuller demean trend lags(3)	Transf. econ (excl. Hungary), Ireland
High correlation— low growth	IPS	$W_{\text{t-bar}}$	*−1.289*	*0.0987*	11	demean trend lags(aic 5)	Transf. econ (excl. Hungary), Ireland
Low correlation— high growth	Fisher	χ^2	26.384	0.0489	8	dfuller demean trend lags(1)	Transf. econ (excl. Hungary), Ireland
Low correlation— high growth	IPS	$W_{\text{t-bar}}$	−1.784	0.0372	8	demean trend lags(aic 2)	Transf. econ (excl. Hungary), Ireland
Low-level MP 1980	Fisher	χ^2	12.655	0.8917	10	dfuller demean lags(5)	Transf. econ (excl. Hungary), Ireland
Low-level MP 1980	IPS	$W_{\text{t-bar}}$	−2.902	0.0019	10	demean trend lags(aic 3)	Transf. econ (excl. Hungary), Ireland
Medium-level MP 1980	Fisher	χ^2	49.804	0.0003	10	dfuller demean lags(1)	Transf. econ (excl. Hungary), Ireland
Medium-level MP 1980	IPS	$W_{\text{t-bar}}$	−3.597	0.0002	10	demean lags (aic 3)	Transf. econ (excl. Hungary), Ireland
Low level of share (%) of service sector 1980	Fisher	χ^2	82.465	0.0000	9	dfuller demean trend lags(3)	
Low level of share (%) of service sector 1980	IPS	$W_{\text{t-bar}}$	−4.668	0.0000	9	demean trend lags(aic 3)	
Low growth of share (%) of service sector 1980–2008	Fisher	χ^2	35.810	0.0075	9	dfuller demean lags(1)	
Low growth of share (%) of service sector 1980–2008	IPS	$W_{\text{t-bar}}$	−3.716	0.0001	9	demean lags (aic 3)	

(continued)

Table 9.11 (continued)

Sample considered	Type	Type of T-stat	Value of T-stat	*p*-value	Number of panels	Specification	Excludes
High growth of share (%) of service sector 1980–2008	Fisher	χ^2	38.555	0.0013	8	dfuller demean trend lags(1)	
High growth of share (%) of service sector 1980–2008	IPS	$W_{\text{t-bar}}$	−5.884	0.0000	8	demean trend lags(aic 3)	

Source: Own calculation based on Global Materialflow Database (2012)

Table 9.12 High correlation: individual unit root test results

ID	Country	Z(*t*)	*p*-value
1	Australia	−1.488	0.8333
5	Chile	−2.762	0.2113
12	Greece	−1.969	0.6181
14	Iceland	−0.994	0.9449
16	Israel	−1.546	0.8130
19	Korea	−1.172	0.9160
20	Mexico	−2.435	0.3610
25	*Portugal*	*−4.812*	*0.0004*
28	*Spain*	*−1.377*	*0.0119*
31	*Turkey*	*−3.907*	*0.0119*
34	Brazil	−0.918	0.9541

Source: Own calculation based on Global Materialflow Database (2012)

On the other hand it is also possible that productive countries are able to retain their advantage and form a convergence club of their own. Empirical evidence of convergence of per capita incomes or life expectancy indicates that this might be the case [see, e.g., Mayer-Foulkes (2001, 2010) or Aghion and Howitt (2009, p. 151)]. In order to test this hypothesis, the log of MP in 1980 was sorted in ascending order and again divided into terciles, tercile 1 again being the tercile with the low level of MP in 1980 and tercile 3 representing the countries with the highest MP in 1980. Again, countries which provided no data for 1980 were excluded; these are the Czech Republic, Estonia, the Slovak Republic, Slovenia, Poland, the Russian Federation, and Ireland. Table 9.14 displays the level of MP in 1980 and the corresponding terciles.

Table 9.13 Low correlation: individual unit root test results

ID	Country	Z(*t*)	*p*-value
3	Belgium-Luxembourg	−1.645	0.7744
4	Canada	−2.800	0.1969
11	*Germany*	*−3.367*	*0.0559*
13	*Hungary*	*−3.659*	*0.0252*
17	Italy	−2.168	0.5079
18	*Japan*	*−3.229*	*0.0787*
23	Norway	−1.124	0.9249
32	UK	−2.704	0.2346

Source: Own calculation based on Global Materialflow Database (2012)

China, Chile, India, Australia, South Africa, Finland, New Zealand, Canada, Brazil, and the USA form the country group with a low level of MP in 1980. If they are considered as a subgroup, one can observe (see Table 9.11 at the end of this chapter) that the Fisher test is not significant, and failure to reject the null hypothesis indicates divergence. In contrast, the IPS test is highly significant indicating that at least a subsample is converging. That these results have to be treated with caution becomes clear when the individual ADF regression results are considered; see Table 9.15. The results seem to be driven by a single highly significant test statistic from Australia, which also might explain why the Fisher and IPS tests do not present the same result.

For the countries with a medium level of MP in 1980, Iceland, Denmark, Hungary, Sweden, Germany, Mexico Korea, Turkey, Austria, and Belgium-Luxembourg, all three tests tend in the same direction, indicating convergence for the whole sample with significant *p*-values throughout. The test results of the Fisher and IPS tests are supported by the individual unit root test results shown in Table 9.16.

Consequently, a sizable subset of the countries in the second tercile of material productivity in 1980 converges in terms of material productivity. Figure 9.3 shows where this group of countries is located in comparison to the overall average material productivity. Those countries comprising the second tercile of the material productivity in 1980 can in 2008 mainly be found above the mean MP of the overall sample.[6]

The countries with a high level of material productivity in 1980 are Italy, France, the UK, Norway, Portugal, Spain, Japan, Israel, Greece, and Switzerland. For those countries both the Fisher and the IPS tests indicated divergence.

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[6] Note that the time-series concept of convergence tested here is a long-run forecast concept, with $t \rightarrow \infty$. Therefore, the convergence clubs might not be visually detectable in this comparably short period of 28 years.

Table 9.14 Level of MP in 1980

Country	logMP 1980	Tercile	Country	logMP 1980	Tercile	Country	logMP 1980	Tercile
China	5.1630	1	Iceland	6.7847	2	Italy	7.0837	3
Chile	5.7952	1	Denmark	6.8614	2	France	7.1237	3
India	5.9090	1	Hungary	6.8716	2	United Kingdom	7.1297	3
Australia	5.9967	1	Sweden	6.8820	2	Norway	7.1368	3
South Africa	6.2675	1	Germany	6.8855	2	Portugal	7.2127	3
Finland	6.2942	1	Mexico	6.9374	2	Spain	7.2968	3
New Zealand	6.3704	1	Korea, Republic of	6.9448	2	Japan	7.2981	3
Canada	6.3809	1	Turkey	6.9613	2	Israel	7.3597	3
Brazil	6.5077	1	Austria	7.0512	2	Greece	7.5187	3
United States	6.7171	1	Belgium Luxembourg	7.0785	2	Switzerland	7.5260	3

Note: Missing: Czech Republic, Estonia, Slovak Republic, Slovenia, Poland, Russian Federation, Ireland

Source: Own calculation based on Global Materialflow Database (2012)

Table 9.15 Low-level MP 1980: individual unit root test results

ID	Country	Z(*t*)	*p*-value
1	*Australia*	*−4.715*	*0.0007*
4	Canada	−1.529	0.8191
5	Chile	−1.771	0.7199
9	Finland	−2.465	0.3458
22	New Zealand	−2.832	0.1853
33	USA	−0.772	0.9680
34	Brazil	−2.879	0.1694
36	India	−2.404	0.3773
38	China	−2.181	0.5007
39	South Africa	−1.754	0.7263

Source: Own calculation based on Global Materialflow Database (2012)

Table 9.16 Medium level of MP 1980: individual unit root test results

ID	Country	Z(*t*)	*p*-value
2	Austria	−2.020	0.5904
3	Belgium-Luxembourg	−2.372	0.3943
7	Denmark	−1.393	0.8630
11	*Germany*	*−4.172*	*0.0049*
13	*Hungary*	*−3.235*	*0.0776*
14	Iceland	−2.526	0.3153
19	Korea	−1.715	0.7442
20	*Mexico*	*−4.982*	*0.0002*
29	Sweden	−0.3003	0.1313
31	Turkey	−2.138	0.5250

Source: Own calculation based on Global Materialflow Database (2012)

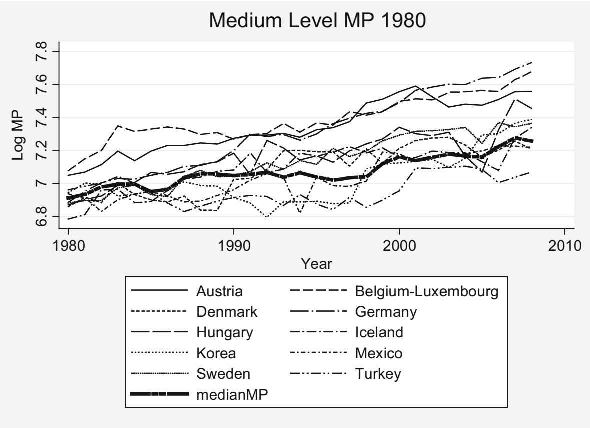


Fig. 9.3 MP development relative to mean (medium level of MP 1980). *Source*: Own calculation based on Global Materialflow Database (2012)

9.3.2.3 Service Sector

Thirdly, the role the service sector plays for convergence club is examined. Generally, an increase of the service sector can be assumed to reduce material consumption. This is due to the fact that a change from industrial production towards more services can generally be assumed to lead to a smaller resource input and may therefore lead to a higher material productivity (Dittrich et al. 2012, p. 41; UNEP 2011a, p. 15). For example, it is quite intuitive that, generally, an economy in which heavy industry contributes a large share to total GDP can be expected to have both a higher material input and a lower material productivity than an economy where the service sector contributes a large share to total GDP. Therefore, the hypothesis that countries with a higher share of the service sector are able to realize a higher level of material productivity is basis for this analysis. The second hypothesis follows from that, namely, that countries which enlarge their service sector are able to realize higher growth rates of MP. This higher growth rate of MP may then fuel a convergence process. This implies two conclusions: firstly, it implies that countries with similar percentage shares of the service sector might form a club with similar performance in terms of material productivity and, secondly, that countries which experienced a similar growth pattern in the service sector also form a club with similar MP developments.

To examine the influence of the share and growth of the service sector of an economy for convergence, the data was again prepared in tabular form, in this case being divided into quartiles. Israel, Greece, Estonia, and the Czech Republic were not included because they did not provide sufficient data. The Russian Federation, the Slovak Republic, Slovenia, and Poland did not provide data in 1980, so for them the earliest data provided was used.

Share of the Service Sector

Table 9.17 displays the percentage share the service sector took up of the whole economy in 1980. Quartile 1 represents the quartile with the lowest share of services, quartile 4 the highest share of the service sector.

The PUR tests for the different quartiles are displayed in Table 9.11 and yielded significant results only for the first quartile, i.e., only the quartile with the lowest percentage share of the service sector in 1980 displays convergence. Starting with the Fisher and the IPS tests, both reject their respective H0, thus indicating that at least some of the countries are converging.

Table 9.18 shows that in this case the rejection of the H0 is driven by two strong rejections and four more rejections at the 35 % level. Thus, the conclusion that a significant subset of the countries in this sample is converging towards each other seems warranted.

In conclusion, a subset of the countries, i.e., China, the Slovak Republic, the Russian Federation, Hungary, India, Poland, Brazil, and South Africa, can be assumed to have formed a convergence club for the period between 1980 and

Table 9.17 Percentage share of service sector in 1980

Country	% Share of service sector in 1980	Quartile	Country	% Share of service sector in 1980	Quartile
China	21.60	1	Turkey	49.68	2
Slovak Republic*	31.94	1	Iceland	51.17	2
Russian Federation*	32.97	1	Portugal	51.56	2
Hungary	33.81	1	Slovenia*	51.94	2
India	40.32	1	Finland	52.00	2
Poland*	41.63	1	Ireland	52.86	2
Brazil	45.16	1	Australia	54.28	2
South Africa	45.43	1	Chile	55.30	2
Korea, Rep.	47.28	1			
Italy	55.91	3	Canada	58.80	4
Spain	56.16	3	New Zealand	58.86	4
Germany	56.54	3	Switzerland	61.15	4
Norway	56.82	3	Belgium-Luxembourg	62.58	4
UK	57.17	3	France	63.27	4
Mexico	57.36	3	USA	63.57	4
Japan	57.89	3	Sweden	63.74	4
Austria	58.77	3	Denmark	67.90	4

Table 9.18 Low level of service sector 1980: individual unit root test results

ID	Country	Z(*t*)	*p*-value
13	Hungary	−2.536	0.3101
19	Korea	−0.957	0.9496
24	*Poland*	*−4.544*	*0.0013*
26	*Slovak Republic*	*−8.977*	*0.0000*
34	Brazil	−2.692	0.2393
35	Russian Federation	−1.282	0.8923
36	India	−2.774	0.240
38	China	−2.137	0.5254
39	South Africa	−2.462	0.3240

Source: Own calculation based on Global Materialflow Database (2012)

2008. These countries achieved only a low level of material productivity when compared to the overall sample. Figure 9.4 shows that the majority of these countries MP lie below the mean MP of the full sample.

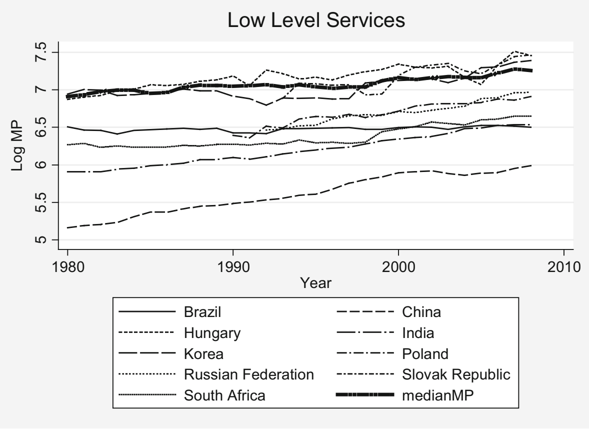


Fig. 9.4 MP development relative to mean (low level of service sector 1980). *Source*: Own calculation based on Global Materialflow Database (2012)

Growth of the Service Sector

For the analysis of the growth of the percentage share of the service sector, the same procedure was applied. Table 9.19 displays the growth rate of the percentage share of the service sector between 1980 and 2008, as well as the according quartiles. Again Estonia, the Czech Republic, Israel, and Greece provided no usable data and are thus excluded. Also, the data start later for the Slovak Republic (1985), the Russian Federation (1989), Slovenia (1990), and Poland (1990), and New Zealand provided data only until 2006.

The PUR tests on the different quartiles of the growth of the service sector yielded statistically significant results for the quartile with the lowest and the quartile with the highest growth of services; see Table 9.11.

For the quartile with the weakest growth of the share of the service sector, the Fisher and IPS tests strongly reject their null hypotheses, indicating that at least some of the countries are converging. This picture is confirmed by the individual unit root test results in Table 9.20. Five out of nine countries exhibit test statistics significant at a 10 % significance level or slightly above, and another two countries' test statistics are significant below 35 % significance.

Figure 9.5 shows that half of the countries in this club exhibit a material productivity above the mean overall material productivity and half of the countries lie below it.

The subsample with the highest growth in the share of the service sector also displays convergence. The Fisher and IPS tests reject their respective H0 and indicate convergence of a greater part of the sample. This conclusion is supported by the unit root test results of the countries, which can be found in Table 9.21. Four countries reject the H0 on 10 % significance level or better and another two countries on a significance level of 23 % or better.

However, in this subsample material productivity in most cases is below the mean MP of the full sample (see Fig. 9.6).

Table 9.19 Growth of service sector between 1980 and 2008

Country	Growth of service sector	Quartile	Country	Growth of service sector	Quartile
Norway	−0.0457508	1	USA	0.2214537	2
Mexico	0.0393609	1	France	0.2244651	2
Chile	0.0465463	1	Slovenia**	0.2250308	2
Denmark	0.0825284	1	Germany	0.2265654	2
Sweden	0.1207028	1	Spain	0.2275146	2
Canada	0.1234623	1	Belgium-Luxembourg	0.2313839	2
Austria	0.1571375	1	Japan	0.2339031	2
Switzerland	0.1627173	1	Finland	0.2517815	2
New Zealand**	0.1814092	1			
Country	**Growth of service sector**	**Quartile**	**Country**	**Growth of service sector**	**Quartile**
Italy	0.2726857	3	Portugal	0.4269633	4
Ireland	0.2727799	3	Australia	0.4292895	4
Turkey	0.2823125	3	Brazil	0.4655138	4
Korea, Republic of	0.2868577	3	Poland**	0.554818	4
Iceland	0.3000598	3	Slovak Republic**	0.7871002	4
UK	0.336353	3	Russian Federation**	0.8039861	4
India	0.3373815	3	China	0.9359056	4
South Africa	0.4082058	3	Hungary	0.9572371	4

Source: Own calculation based on Global Materialflow Database (2012)

Note: Missing—Czech Republic, Estonia, Israel, Greece. **Slovak Republic (1985), Russian Federation (1989), Slovenia (1990), Poland (1990), New Zealand (2006)

Table 9.20 Low growth service sector: individual unit root test results

ID	Country	Z(*t*)	*p*-value
2	*Austria*	*−3.114*	*0.0255*
4	Canada	−0.981	0.7600
5	Chile	−1.605	0.4813
7	Denmark	−2.370	0.1503
20	*Mexico*	*−2.543*	*0.1053*
22	New Zealand	−1.969	0.3003
23	*Norway*	*−2.469*	*0.1232*
29	*Sweden*	*−3.148*	*0.0232*
30	*Switzerland*	*−2.435*	*0.1321*

Source: Own calculation based on Global Materialflow Database (2012)

Fig. 9.5 MP development relative to mean (low growth of service sector). *Source*: Own calculation based on Global Materialflow Database (2012)

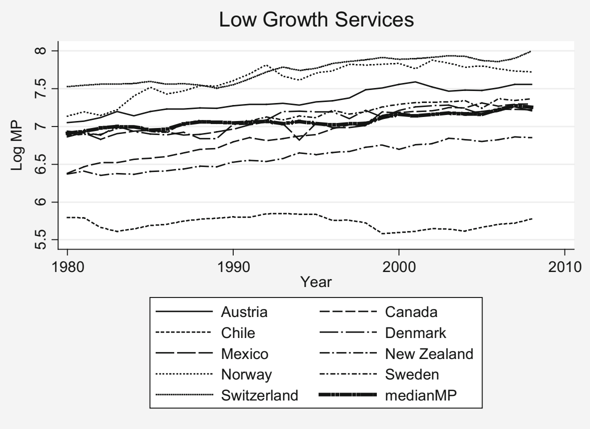
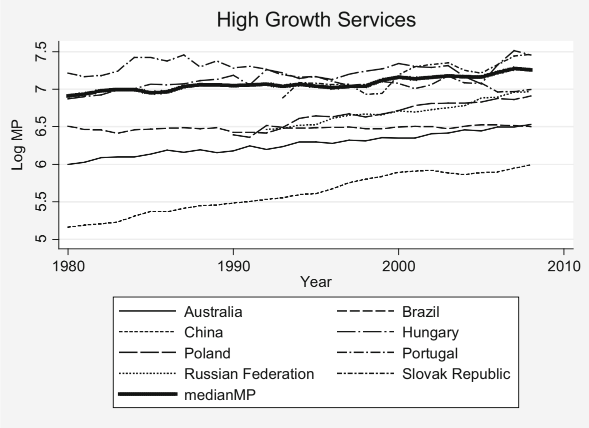


Table 9.21 High growth service sector: individual unit root test results

ID	Country	Z(*t*)	*p*-value
1	*Australia*	*−3.721*	*0.0210*
13	*Hungary*	*−3.191*	*0.0862*
24	Poland	−2.728	0.2246
25	Portugal	−2.832	0.1853
26	*Slovak Republic*	*−3.808*	*0.0162*
34	*Brazil*	*−3.900*	*0.0121*
35	Russian Federation	−2.225	0.4760
38	China	−1.997	0.6029

Source: Own calculation based on Global Materialflow Database (2012)

Fig. 9.6 MP development relative to mean (high growth of service sector). *Source*: Own calculation based on Global Materialflow Database (2012)



Chapter 10
Discussion

In the previous chapter material productivity convergence was analyzed. σ-Convergence and β-convergence were analyzed. For β-convergence, first cross-sectional and panel regression analysis and, following that, time-series analysis were conducted. The results of these analyses are very diverse. This chapter presents a compilation and discussion of them.

The analysis showed that σ-convergence is absent for the full country sample between 1980 and 2008, and instead, σ-divergence took place. However, when this result is examined more closely, it is apparent that a phase of σ-convergence was followed by a period of divergence from 1995. This means that the variation between the countries decreased between 1980 and 1994, yet from 1995 onwards the variation increased again, overcompensating for the previous improvements.

Analysis showed that most of the samples considered did not display unconditional β-convergence and the model fit and coefficient significance were low. The only significant results were obtained for the BICS and the OECD countries. However, the methods applied to derive these results differ; the results for the BICS countries were obtained using a cross section of data, whereas the results for the OECD countries originate in a panel setup. In addition, the development patterns revealed for these two country groupings differ. The BICS countries display unconditional β-convergence, indicating that within the group comprising Brazil, India, China, and South Africa, countries with a lower MP were able to improve their productivity to a greater extent than more productive countries. Using a cross-sectional framework β-divergence was identified for the OECD countries, suggesting that more productive OECD countries were able to improve their MP faster than less productive countries, i.e., no catching up took place. The analysis of conditional β-convergence by means of panel methods indicated β-divergence for the full sample and the OECD countries. This suggests, just as the cross-sectional analysis implied, that countries with a higher MP were able to increase their MP to a greater extent than their less productive counterparts, thus magnifying existing disparities.

Overall, regarding analysis of β-convergence, it can be recorded that in the sample consisting of the OECD and BRICS countries, there is generally no

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tendency for countries with a lower material productivity to improve their MP faster than countries with a higher material productivity.

Opposed to that, the panel unit root tests indicated conditional β-convergence for a sizable subset of the full sample as well as for the transformation economies. As Bernard and Durlauf (1996) argued, different convergence approaches are subject to different assumptions with regard to the position of a country approaching the steady state. Therefore, the results for the OECD countries might be more valid if they were derived from time-series concepts. The data for the BRICS/BICS and transformation economies may be characterized by transition rather than steady-state dynamics, and therefore, consideration of results derived from cross-sectional analysis may be more appropriate in this context.

As mentioned in Sect. 4.2 following the argument of Bernard and Durlauf (1996), it can be concluded that the result of β-convergence for the BICS countries in the cross-sectional setup may be more acceptable than the result of β-convergence for the transformation economies in a time-series context. However, as mentioned above, the cross-sectional methods are subject to a number of limitations as mentioned earlier; thus, the results for the BICS countries should only be cautiously accepted.

The analysis of material productivity convergence by means of panel unit root test suggests that a significant subset of the overall sample displays convergence. Also, when the transformation economies are analyzed separately, convergence can be found. Separate examination of the OECD and BRICS countries yielded divergence of material productivity.

The results of convergence-club analysis by panel unit root tests can be found in Table 10.1. It lists all subsamples, as defined in Chap. 9, for which club convergence could be identified, and relates them to their level of material productivity performance in comparison to the full sample.

This shows that among the samples for which convergence club could be identified, there is only one subsample located in the middle of the distribution of the respective grouping criteria, namely, the club with a medium MP in 1980. The remaining convergence clubs are all located at the "extremes," thus either in the top or bottom quantile.

Table 10.1 also shows how the convergence-club subsamples relate to material productivity. This information is drawn from Figs. 9.3 to 9.6. The convergence level of material productivity lies above the mean or median in two cases, respectively: in the low correlation-high growth club and in the club with medium MP in 1980. For clubs with a low initial level and high growth of the service sector, a low level of material productivity is found; two-thirds of the countries of these clubs can be found in the bottom half of material productivity performance in 2008. For the club exhibiting a low level of service sector, growth MP performance is very poor. Four out of nine countries in this club exhibit a material productivity in the lowest quarter of MP performance. Thus, again, a polarization at the top and bottom end of

Table 10.1 Summary of PUR test results—convergence clubs

Subsample	Level of material productivity (relative of median/mean of full sample)
High correlation—low MP growth	Below median
Low correlation—high MP growth	Above median
Medium MP in 1980	Above mean
Low % share of services	Below mean
Low growth % share of services	50 % below, 50 % above mean
High growth % share of services	Below mean

Source: Own illustration

material productivity can be identified.[1] This has implications for the non-converging countries: MP levels of those countries will heavily depend upon whether they can attach to a club and to which club. If they become part of a convergence club with generally higher levels of MP, their MP levels can be expected to become assimilated with those of the club. If they become part of a club with low levels of MP, convergence will also take place but at a lower level of MP. The existence of low level convergence clubs is undesirable in terms of efficient resource use. However, further analysis is required to examine whether the performance of these low-level clubs can be improved by policy measures or if these countries have little room for improvement and their position is primarily determined exogenously, e.g., by their position within the international division of labor.

Another observation with regard to convergence clubs is that when the three convergence clubs relating to the service sector are considered and a comparison made of the countries that form these clubs, it becomes apparent that these three clubs may actually comprise only two clubs. The club consisting of countries with a low share of the service sector in 1980 and the club of countries with a high service sector growth rate are very similar. In fact, they have six out of nine members in common: Hungary, Poland, the Slovak Republic, Brazil, the Russian Federation, and China.

Limitations of the analysis arise from a number of different issues. One limitation concerns the indicator for material productivity: Generally, if material productivity is considered as a part of total factor productivity, the indicator of choice for an analysis of MP convergence should reflect technology. Until recently, the only MP indicator available and that used in this dissertation focuses more on consumption than on inputs. DMC includes only domestic production and thus production technology that remains domestic, i.e., it does not get exported. However, for an

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[1] This finding is in line with a recent study by Camarero et al. (2013) who examined eco-efficiency and convergence in the OECD and also identified convergence club for the most eco-efficient as well as for the least eco-efficient countries in the sample.

analysis of production technology, an input indicator would be preferable. Conducting the analysis again using a productivity indicator based on the direct material input (DMI) might provide more valid inferences regarding the relationship between MP and TFP. Despite these limitations, the material productivity indicator based on material consumption has been selected by the European Union as the indicator for productivity measurement.

Also, even if material productivity converges, increases in MP do not automatically imply a reduction of material consumption levels. For instance, material productivity can improve even if material consumption increases, if gross domestic product increases to a greater extent than material consumption.

Additionally, material productivity improvements may lead to a "rebound effect," thus subsequently increasing material consumption. Whether material consumption levels can actually be reduced depends on a range of factors driving gross domestic product and economic growth, as well as material consumption levels and growth. Further systematic analyses of the relationship between the individual factors driving the components of MP are necessary. This is especially relevant given the importance of material consumption levels in the context of sustainable development.

Another limitation of the convergence-club analysis is that grouping the countries according to terciles or quartiles may be to some extent arbitrary. Also, the growth of the service sector may not be strictly comparable between all countries in the sample, as for some countries data was only available post 1980. Moreover, the panel unit root tests are subject to a number of limitations and problems especially concerning structural breaks in the data.

To sum up, the analysis of MP development patterns does not suggest the existence of some uniform "mechanism" which results in similar high levels of material productivity for all countries. Rather, convergence could be identified only in some cases. This convergence, however, only occurred for subsamples and/or subperiods. In addition, the analysis of convergence club showed that it did not occur for all countries in the sample, but primarily for countries at the upper and lower end of the respective distributions.

The results of this dissertation suggest that policies to reduce global material consumption need to pursue two goals: reducing material consumption, for instance, through intelligent product design, "top runner programs," or consumer information, and convergence of material productivity via technology policies which facilitate technology transfer and diffusion. The combination of these two policy types can aim at (1) increasing material productivity through the implementation of material efficient technologies worldwide and (2) simultaneously reducing material consumption. The results of this dissertation also suggest that the efforts in both of these areas need to be increased in order to achieve a reduction of material consumption. However, in light of the fact that the policies have not been pursued for a long time yet, a reevaluation of convergence patterns at a later point in time is advisable.

Given that the entire topic of material productivity analysis is a rather "young" research area and that data has only recently become publicly available, this study can only be a starting point for further analysis. Further research areas requiring examination include analysis of the mobility patterns between the different convergence clubs, as well as the factors influencing this mobility. Also, analysis of the performance of convergence clubs with low levels of MP might provide interesting insights into whether their performance can be improved, for instance, by policy measures, or whether their performance is determined primarily by their position within the international distribution of labor. Moreover, case study type analyses examining whether and how policies and/or best practices from leading countries can be transferred to lagging countries between the clubs could also contribute to an improvement in the understanding of material productivity.

Chapter 11
Conclusion

Natural resources continue to be a topic of interest in the present public and academic debate. Natural resources are not only input factors for the production of goods and services, they are also the very basis of life itself providing food, clothing, and shelter as well as services like clean air to breathe or water to drink. During the course of the twentieth century, material use increased substantially (Krausmann et al. 2009). This increased extraction and use of materials has had consequences on income and welfare levels as well as on ecosystems and landscapes. Society and the economy are embedded in the environment, and everything that is extracted from the environment, for instance, for purposes of production and consumption at some point in time, returns as an output into the environment again. Thus, with increasing material extraction outputs to the environment also increase. Prominent examples of environmental pressures are periodically discussed in public, such as the Deepwater Horizon oil spill in the Gulf of Mexico in 2010, overexploited global fish stocks, or the very poor and even dangerous air quality in cities like Beijing in spring 2013. Scarcity of resources is another concern linked with increasing extraction of materials from the environment. Economists have argued that for nonrenewable resources such as metal ores or minerals, “we shall never run out” (Tietenberg and Lewis 2009, p. 604). Yet, scarcity and thus price increases of strategic materials like the so-called rare earths have increasingly become a concern for businesses [see, for instance, Liebrich (2010), Kiani-Kress (2012), or Iw-Dienst (2011)]. In addition to these discussions, the overuse of renewable natural resources features less prominently in the public domain. Still, it is of major interest in the context of sustainability, as overuse of renewable resources such as freshwater, fish stocks, or ecosystem services can lead to the subsequent collapse of stocks or ecosystems, from which they might not be able to recover. As a consequence of all these issues, a range of policies and strategies have been adopted aiming to decouple or de-link resource use and thus the environmental consequences of resource use from economic growth. A first step towards this goal is the more efficient use of natural resources or materials.

The efficiency of material use is the concern of this dissertation. Specifically, material productivity, i.e., the efficiency with which materials are used in

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production and consumption, is considered. This dissertation asks if the development of material productivity displays empirical regularities following a specific, common pattern so that eventually, the levels (and growth rates) of material productivity will assimilate. This is known as convergence analysis.

In the first part of this dissertation, the theoretical foundations for an analysis of convergence of material productivity were laid out. In the first chapter some basic definitions with regard to natural capital and natural resources were provided.

Chapter 2 provided an overview of five exemplary areas in which overuse of natural capital is particularly evident and the major issues arising within each of them. Those five areas include climate change; the overuse of renewable resources; the use of nonrenewable resources and its consequences; the destruction of ecosystems, species, and landscapes; and threats to human health. This chapter also briefly presented the reasons for overuse of natural capital, mainly from an economic point of view. Possibly the most important issue in this context is the absence of properly defined property rights, as is the case for open-access resources. If property rights of natural or material resources are not well defined, externalities may occur. In this case the marginal cost of production will be larger for society than they are for the producer. As a consequence, natural resources are not efficiently allocated, which in turn may lead to overuse. When property rights are not defined at all, resources can be exploited on a first-come first-served basis. There are no incentives to conserve the resource as scarcity rents cannot be appropriated by anyone. So if demand is high, the resource will be overused. Similarly, the public good characteristics displayed by some natural resources are one reason for their overuse. Public goods are characterized by non-excludability, i.e., nobody can be excluded from the consumption of a public good regardless of whether he or she has paid for it, and by indivisibility, i.e., one person's consumption does not diminish the consumption possibilities of another person. Examples of public goods are clean air or clean water. The consequences of these special characteristics are a supply that is smaller than it would be efficient or overuse, as scarcities are not reflected in prices. However, there is a variety of other contributing factors. Given the development of global population, economic growth and development patterns such as economic structure, production and consumption patterns, or technology resource use can be expected to increase over the coming decades, which will intensify existing scarcities. Consequences of the overuse of natural resources include not only price increases but also more universal and permanent environmental damages and a higher likelihood of nonlinear changes in ecosystems or loss of biodiversity.

The insight that overuse of natural resources has far-reaching consequences also leads to the debate about sustainability and associated policies. Section 2.2 reviewed the debate about sustainable development as well as discussed the most recent policies in this context. One example is the OECD strategy for "green growth." This strategy aims at promoting greener behavior of firms and consumers, the reallocation of technology and capital towards greener activities, as well as the provision of incentives and support for green innovation. The efficient use of natural resources is a central element of this policy. In order to measure progress towards "green growth" in general, the OECD proposes a set of indicators. The efficient use of natural resources is measured by a resource efficiency indicator. Similarly, the European Union adopted this as lead indicator for its Flagship Initiative for a Resource Efficient Europe. Section 2.2 highlighted that technology and innovation are the central components for "green growth" and an increase of resource efficiency.

Therefore, the relationship between technological progress and material consumption was revised in Chap. 3. The so-called eco-innovations or green innovations play a major role in reducing natural resource use. They can be defined as an innovation "that reduces the use of natural resources [. . .] and decreases the release of harmful substances across the whole life-cycle" (Eco-Innovation Observatory 2012, p. 8). Often they are also categorized according to whether they are end-of-pipe technologies or integrated technologies. End-of-pipe technologies are technologies used after the production of goods, for instance, disposal processes and recycling technologies. Integrated technologies, on the other hand, are used in the production of goods aiming at reducing material and energy input as well as emissions. Another characteristic of eco-innovations as well as innovations in general is the occurrence of two forms of externalities associated with them. Firstly, knowledge spillovers cause positive externalities, as the returns on the investment in eco-innovations benefit not only the investor but also the society at large. However, this may cause the rate of innovation to be below optimal. Secondly, environmental impacts cause negative externalities, as polluters receive the full benefit of using the environment but do not bear the full costs of using it. Consequently, innovation will be more pollution intensive than it would if prices were not distorted. Innovation and environmental policy measures can be used to remedy these externalities. More generally, environmental policies aim to either change the cost of factor inputs or change the relative price of goods and services produced. The cost of a factor input is changed, for instance, if producers are required to buy CO_2 emission certificates for their production. The relative price of goods is changed, for example, by introducing a tax on fossil fuels. These changes in costs and prices are likely to lead to environment-saving production processes and products. The theory of induced innovation implies that environmental policy can induce eco-innovations and consequently pressures on the environment can be diminished.

Given the central role of the idea of induced innovations for environmental policies, they were discussed in more detail in Sect. 3.2. This chapter presented the basic idea of induced innovations, i.e., that a change in the relative price of a good will change both consumption patterns and the direction of technological progress. For example, if energy prices rise relative to the price of other goods, people will change their behavior and turn down thermostats, drive slower, or replace furnaces with more efficient models. Over the long run, this will cause a change in the direction of technical change in the way that the capital goods available for purchase will consist of more energy-efficient choices (Newell et al. 1999). The same idea can be applied to other inputs from natural resources. The idea of induced innovation goes back to Hicks, who claimed that "a change in the relative prices of the factors of production is itself a spur to inventions of a particular kind—directed at economising the use of a factor which has become relatively expensive" (Hicks 1948, p. 124). The reappearance of the topic in the early 1960 sparked a discussion, which was briefly outlined in this chapter. Also, the basic ideas of two major approaches to the model of induced innovation—the macroeconomic and the microeconomic approach—were presented. Section 3.2 also briefly touches on the topic of labor market effects of technological progress and the parallels that can be drawn from this debate relating to the debate about natural-resource-augmenting technological progress. Unemployment that is caused by technological progress is sometimes termed "technological unemployment." While in the case of labor markets this is an undesirable phenomenon, in the area of natural resources, it is not. Innovations for reducing natural resource use basically aim at steering technological progress in a direction, so it becomes resource augmenting and thus makes natural resources "unemployed" via technological progress.

The next two chapters presented the methods for a systematic analysis of material productivity convergence. In Chap. 4 the concept of convergence, existing empirical evidence, as well as the econometric tools for examining convergence were introduced. Firstly, the Solow–Swan growth model, which is the starting point for most analyses of convergence, was presented as well as the two concepts of β-convergence and σ-convergence and the distinction between conditional and absolute β-convergence. Secondly, a variant of a Schumpeterian endogenous growth model was discussed. In this type of model, convergence can occur through both technological progress and capital accumulation. In Sect. 4.2 the econometrics for measuring convergence were reviewed. First, the basics of convergence analysis were presented including the econometric definition of convergence. Next, the relationship between the Solow model and the econometric formulation of β-convergence was described. The next section explained how the use of panel data and the inclusion of fixed effects can help to overcome some problems such as the omitted variable bias. This section is followed by a review of the limitations that analyses of β-convergence are generally subject to. One of the shortcomings addressed in this section is that β-convergence cannot answer the question of whether levels of per capita incomes or any other variable of interest assimilate over time (Hemmer and Lorenz 2004). This question can be answered by means of time-series approaches, which are discussed in Sect. 4.2.3. This section started with the basics of convergence analysis in a time-series context as well as a convergence definition in a time-series framework. Next, a strategy for analyzing convergence in a macro panel by means of panel unit root tests following Evans (1998) was presented. The theory of panel unit root tests as well as two different panel unit root tests by Im et al. and by Maddala and Wu were introduced, and their limitations were discussed. The chapter on the econometrics of convergence concludes with a brief summary of the econometrics of σ-convergence. Section 4.3 presented a number of empirical studies on convergence of different economic variables. Most of convergence studies deal with convergence of per capita incomes and productivity, but the chapter also mentioned convergence analyses of other variables such as life expectancy, energy productivity, and CO_2 emissions. With regard to the results of per capita convergence, it appears that the finding of β-convergence is relatively robust. σ-Convergence can mostly be found in those country samples which also display unconditional β-convergence (Islam 2003b).

Chapter 5 presented the methods for measuring material productivity. In order to measure material productivity, information on material use is combined with GDP data. The method of measuring material use, the so-called material flow analysis, was introduced first. The section on material flow analysis started by laying out the intellectual origins of material flow analysis, its basic concept, as well as its uses. Next, material flow input and consumption indicators and resulting efficiency indicators were introduced before the major limitations of material flow analysis were discussed. The second part of Chap. 5 was dedicated to the measurement of productivity by means of productivity indicators. Firstly, the uses of productivity analysis were presented and the basics of productivity measurement were summarized. This also included the distinction between and a description of single-factor productivity measures and multifactor productivity measures. The section on productivity measurement concluded with the discussion of measurement issues which occur relating to productivity indicators. The last chapter of the theoretical part of the dissertation provided a summary of empirical studies on the state and development of material consumption and material productivity. Reviewing different studies showed that material use and efficiency of material use differ strongly between countries. It also showed that the major focus of empirical studies had so far been the description of the data.

In the second part of the dissertation, an empirical analysis of material productivity convergence was conducted. However, firstly the research question was re-clarified and the motivation for an analysis of material productivity convergence was presented.

Insights about empirical regularities of material productivity development can, on the one hand, contribute to a better understanding of aggregate productivity development. On the other hand, and more importantly in the context of this dissertation, it can contribute to the debate about sustainable development. Material productivity developments are of increasing interest in light of the requirement for material productivity to grow faster than the economic output in order to decouple economic growth from material use. The presence or absence of convergence of material productivity thus has several implications for a reduction of overall material use. Generally, increases in material productivity generate ceteris paribus, a potential for a reduction of global material consumption. Presence or absence of convergence of material productivity has implications for this potential for reduction. The different implications of convergence of growth rates (β-convergence) and levels (time-series concepts) were discussed as well as the implications of non-convergence. Presence of β-convergence allows additional benefits in terms of material productivity to be realized internationally as less productive countries are able to improve their performance to a greater extent than more productive countries. If material productivity levels converge at a high level, the potential for a reduction of international material consumption is increased. On the contrary, this potential is diminished if convergence takes place at a low level of material productivity. Generally, non-convergence in both levels and growth rates implies that there is no potential for an additional reduction of material consumption.

Chapter 8 presents the data for the analysis, its sources and limitations, as well as first descriptive statistics and analyses. The descriptive, graphical analysis of material productivity convergence in the OECD and BRICS countries between 1980 and 2008 indicated that material productivity follows different phases of transition while improving over time. With regard to σ-convergence, a pattern of convergence seems to be followed by a pattern of divergence at medium levels of average material productivity, while a convergence pattern can be observed at high levels of material productivity. A similar pattern can be found for β-convergence. However, at high levels of average material productivity, no convergence pattern can be observed; instead, the process seems to freeze and neither convergence nor divergence occurs.

An analysis of material productivity convergence by regression and time-series analysis was conducted in Chap. 9. Firstly, σ-convergence of material productivity was examined. This analysis revealed patterns of divergence; thus, differences in material productivity between the economies of the sample increased over time. In Sect. 9.2 β-convergence of material productivity was analyzed by cross section as well as by panel methods. The cross-sectional analysis revealed unconditional convergence only for the country group consisting of Brazil, India, China, and South Africa between 1980 and 2008. This process of unconditional β-convergence possibly contributed to the process of σ-convergence identified earlier for this country group. This finding is in line with other findings of σ-convergence for samples with unconditional β-convergence of per capita incomes. For the entire sample as well as other groupings such as the OECD countries, or the transformation economies of the OECD countries, no significant estimates were obtained. The panel analysis of conditional β-convergence yielded divergence for both the full sample as well as for the OECD countries. Thus, more productive countries were able to increase their material productivity faster than less productive countries over the period 1980–2008.

Time-series methods were used in Sect. 9.3 to overcome the limitations of cross-sectional and panel analyses of convergence of material productivity. Analysis of the overall sample showed that some convergence takes place on the aggregate level. The results for the full sample as well as for the transformation economies of the OECD countries suggested that a significant subset of those country groups converged towards each other. Next, it was examined whether convergence club takes place in the countries under consideration. Three possible club determinants were chosen according to which the countries were grouped.

Firstly, the countries were divided into clubs according to a pattern suggested by the visual inspection of the graphs of the development of GDP, DMC, and material productivity. In this case countries were selected according to the correlation displayed by GDP and DMC as well as their growth rate of material productivity, and consequently two groups were formed. The convergence analysis for these groups showed that a significant subset of the countries within these groups converge towards each other. Secondly, following Gerschenkron's hypothesis of economic backwardness (Gerschenkron 1962), the role played by the initial level of material productivity was examined. Analysis of the three groups constructed showed that only the group with a medium initial level of material productivity seems to converge. Finally, the role played by the share of the service sector and its development was examined. The countries were grouped according to the share occupied by the service sector as percentage of total GDP as well as according to the growth rate of the share of the service sector of total GDP between 1980 and 2008. The results of the convergence analysis suggested that only the group with a low level of services of total GDP as well as the groups with high and low growth rates of the service sector displayed convergence. It has to be noted, however, that the club with a low share of the service sector in 1980 and the club with a high growth rate of the share of the service sector are quite similar with regard to the countries they consist of. From the nine countries that each club consists of, six countries are the same in both clubs. The two clubs may actually be the same club (with a slight variation) only that it is identified on the basis of two different characteristics. For the remaining country groups, divergence is implied by the failure to find convergence.

The results for the convergence club also show that only one of the converging groups is located in the middle with respect to the respective grouping characteristics, while the other converging groups can either be found in the top or the bottom quantile. Thus, if convergence takes place, it appears to occur for those countries either on top or on the bottom of the distribution. The countries lying in the middle of the distribution do not seem to display convergence. The level of material productivity that is associated with the convergence clubs relative to the mean material productivity of the full sample was also considered in order to shed light on possible implications for global material use. This analysis shows that of the clubs that could be identified, only two clubs converge to a high, i.e., above mean or median level of material productivity, namely, the club with the medium level of material productivity in 1980 and the club with a low correlation between GDP and DMC and high MP growth. In the remaining three clubs, the majority of countries seem to converge towards either a low or very low level of material productivity. Of the clubs with a low share of the service sector in 1980 and the club with a high growth rate of the service sector, around two thirds of the countries material productivity can be found below the overall mean. In the club with the low growth rate of the service sector, almost half of the countries display a material productivity below the 25 % percentile of the overall sample in 2008. Thus, the convergence processes that take place are polarized at the top and the bottom level of material productivity. This implies that for the diverging middle group, it is crucial if they are able to attach to a club, and if they do so, to which club they attach to. If they become part of the convergence club with a relatively high level of MP, it is likely that they will be able to improve their MP performance. However, if they attach to one of the clubs with low MP, their MP is more likely to remain lower.

Overall, these results indicate the importance of technology diffusion for an improvement of global material productivity. This is in line with existing policy recommendations which aim to both increase material productivity through the implementation of material efficient technologies and simultaneously reduce material consumption via established environmental policy measures. The results of this dissertation also suggest that the efforts of both policy areas need to be intensified in order to achieve a reduction of material consumption.

Appendix

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Augmented Dickey–Fuller Test Results for log MP

Australia

```
Dickey-Fuller test for unit root                Number of obs   =       28

                          ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical     5% Critical    10% Critical
           Statistic       Value          Value
Value
------------------------------------------------------------------------------
 Z(t)          -0.720          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.8414
```

Austria

```
Dickey-Fuller test for unit root                Number of obs   =       28

                          ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical     5% Critical    10% Critical
           Statistic       Value          Value
Value
------------------------------------------------------------------------------
 Z(t)          -1.271          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.6424
```

Belgium Luxembourg

```
Dickey-Fuller test for unit root                Number of obs   =       28

                          ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical     5% Critical    10% Critical
           Statistic       Value          Value
Value
------------------------------------------------------------------------------
 Z(t)          -1.125          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.7049
```

Brazil

```
Dickey-Fuller test for unit root              Number of obs   =       28

                      ---------- Interpolated Dickey-Fuller ---------
              Test       1% Critical      5% Critical     10% Critical
           Statistic        Value           Value
Value
------------------------------------------------------------------------
 Z(t)          -2.500          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.1154
```

Canada

```
Dickey-Fuller test for unit root               Number of obs   =       28

                      ---------- Interpolated Dickey-Fuller ---------
              Test       1% Critical      5% Critical     10% Critical
           Statistic        Value           Value
Value
------------------------------------------------------------------------
 Z(t)          -1.399          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.5826
```

Chile

```
Dickey-Fuller test for unit root               Number of obs   =       28

                      ---------- Interpolated Dickey-Fuller ---------
              Test       1% Critical      5% Critical     10% Critical
           Statistic        Value           Value
Value
------------------------------------------------------------------------
 Z(t)          -1.634          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.4654
```

China

```
Dickey-Fuller test for unitroot                Number of obs   =       28

                         ---------- Interpolated Dickey-Fuller ---------
            Test       1% Critical      5% Critical     10% Critical
          Statistic       Value          Value
Value
------------------------------------------------------------------------
 Z(t)         -1.089          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.7193
```

Czech Republic

```
Dickey-Fuller test for unit root                Number of obs   =       15

                         ---------- Interpolated Dickey-Fuller ---------
            Test       1% Critical      5% Critical     10% Critical
          Statistic       Value          Value
Value
------------------------------------------------------------------------
 Z(t)         -0.771          -3.750          -3.000          -2.630
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.8276
```

Denmark

```
Dickey-Fuller test for unit root                Number of obs   =       28

                         ---------- Interpolated Dickey-Fuller ---------
            Test       1% Critical      5% Critical     10% Critical
          Statistic       Value          Value
Value
------------------------------------------------------------------------
 Z(t)         -1.547          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.5104
```

Estonia

```
Dickey-Fuller test for unit root              Number of obs   =      13

                    ---------- Interpolated Dickey-Fuller ---------
            Test       1% Critical     5% Critical     10% Critical
          Statistic       Value           Value
Value
------------------------------------------------------------------------------
 Z(t)          -1.188          -3.750          -3.000          -2.630
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.6787
```

Finland

```
Dickey-Fuller test for unit root              Number of obs   =      28

                    ---------- Interpolated Dickey-Fuller ---------
            Test       1% Critical     5% Critical     10% Critical
          Statistic       Value           Value
Value
------------------------------------------------------------------------------
 Z(t)          -1.035          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.7401
```

France

```
Dickey-Fuller test for unit root              Number of obs   =      28

                    ---------- Interpolated Dickey-Fuller ---------
            Test       1% Critical     5% Critical     10% Critical
          Statistic       Value           Value
Value
------------------------------------------------------------------------------
 Z(t)          -2.515          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.1118
```

Germany

```
Dickey-Fuller test for unit root                Number of obs   =       28

                        ---------- Interpolated Dickey-Fuller ---------
              Test       1% Critical     5% Critical     10% Critical
            Statistic       Value           Value
Value
------------------------------------------------------------------------------
 Z(t)          -0.488          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.8943
```

Greece

```
Dickey-Fuller test for unit root                Number of obs   =       28

                        ---------- Interpolated Dickey-Fuller ---------
              Test       1% Critical     5% Critical     10% Critical
            Statistic       Value           Value
Value
------------------------------------------------------------------------------
 Z(t)          -2.651          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.0829
```

Hungary

```
Dickey-Fuller test for unit root                Number of obs   =       28

                        ---------- Interpolated Dickey-Fuller ---------
              Test       1% Critical     5% Critical     10% Critical
            Statistic       Value           Value
Value
------------------------------------------------------------------------------
 Z(t)          -1.654          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.4549
```

Iceland

```
Dickey-Fuller test for unit root              Number of obs   =       28

                    ---------- Interpolated Dickey-Fuller---------
            Test       1% Critical     5% Critical    10% Critical
          Statistic       Value          Value
Value
-----------------------------------------------------------------------
 Z(t)         -1.789         -3.730         -2.992         -2.626
-----------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.3861
```

India

```
Dickey-Fuller test for unit root              Number of obs   =       28

                    ---------- Interpolated Dickey-Fuller ---------
            Test       1% Critical     5% Critical    10% Critical
          Statistic       Value          Value
Value
-----------------------------------------------------------------------
 Z(t)          0.659         -3.730         -2.992         -2.626
-----------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9890
```

Ireland

```
Dickey-Fuller test for unit root              Number of obs   =        8

                    ---------- Interpolated Dickey-Fuller ---------
            Test       1% Critical     5% Critical    10% Critical
          Statistic       Value          Value
Value
-----------------------------------------------------------------------
 Z(t)         -0.858         -3.750         -3.000         -2.630
-----------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.8015
```

Israel

```
Dickey-Fuller test for unit root               Number of obs   =       28

                     ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical     5% Critical     10% Critical
           Statistic       Value           Value
Value
------------------------------------------------------------------------
 Z(t)          -1.436          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.5650
```

Italy

```
Dickey-Fuller test for unit root               Number of obs   =       28

                     ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical     5% Critical     10% Critical
           Statistic       Value           Value
Value
------------------------------------------------------------------------
 Z(t)           0.517          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9854
```

Japan

```
Dickey-Fuller test for unit root               Number of obs   =       28

                     ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical     5% Critical     10% Critical
           Statistic       Value           Value
Value
------------------------------------------------------------------------
 Z(t)          -2.186          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.2115
```

Korea, Republic of

```
Dickey-Fuller test for unit root                Number of obs   =       28

                         ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical      5% Critical    10% Critical
            Statistic       Value            Value
Value
--------------------------------------------------------------------------
 Z(t)          0.242          -3.730          -2.992          -2.626
--------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9745
```

Mexico

```
Dickey-Fuller test for unit root                Number of obs   =       28

                         ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical      5% Critical    10% Critical
            Statistic       Value            Value
Value
--------------------------------------------------------------------------
 Z(t)         -1.301          -3.730          -2.992          -2.626
--------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.6285
```

Netherlands

```
Dickey-Fuller test for unit root                Number of obs   =       28

                         ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical      5% Critical    10% Critical
            Statistic       Value            Value
Value
--------------------------------------------------------------------------
 Z(t)         -2.967          -3.730          -2.992          -2.626
--------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.0381
```

New Zealand

```
Dickey-Fuller test for unit root                 Number of obs   =       28

                   ---------- Interpolated Dickey-Fuller ---------
             Test        1% Critical      5% Critical     10% Critical
           Statistic        Value            Value
Value
------------------------------------------------------------------------------
 Z(t)          -0.421          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9065
```

Norway

```
Dickey-Fuller test for unit root                 Number of obs   =       28

                   ---------- Interpolated Dickey-Fuller ---------
             Test        1% Critical      5% Critical     10% Critical
           Statistic        Value            Value
Value
------------------------------------------------------------------------------
 Z(t)          -2.333          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.1616
```

Poland

```
Dickey-Fuller test for unit root                 Number of obs   =       18

                   ---------- Interpolated Dickey-Fuller ---------
             Test        1% Critical      5% Critical     10% Critical
           Statistic        Value            Value
Value
------------------------------------------------------------------------------
 Z(t)          -1.283          -3.750          -3.000          -2.630
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.6369
```

Portugal

```
Dickey-Fuller test for unit root                 Number of obs   =      28

                      ---------- Interpolated Dickey-Fuller ---------
            Test        1% Critical     5% Critical     10% Critical
          Statistic        Value           Value
Value
---------------------------------------------------------------------------
 Z(t)         -1.081          -3.730          -2.992          -2.626
---------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.7226
```

Russian Federation

```
Dickey-Fuller test for unit root                 Number of obs   =      16

                      ---------- Interpolated Dickey-Fuller ---------
            Test        1% Critical     5% Critical     10% Critical
          Statistic        Value           Value
Value
---------------------------------------------------------------------------
 Z(t)         -0.056          -3.750          -3.000          -2.630
---------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9537
```

Slovak Republic

```
Dickey-Fuller test for unit root                 Number of obs   =      15

                      ---------- Interpolated Dickey-Fuller ---------
            Test        1% Critical     5% Critical     10% Critical
          Statistic        Value           Value
Value
---------------------------------------------------------------------------
 Z(t)         -1.222          -3.750          -3.000          -2.630
---------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.6642
```

Slovenia

```
Dickey-Fuller test for unit root                Number of obs   =       16

                         ---------- Interpolated Dickey-Fuller ---------
              Test        1% Critical      5% Critical     10% Critical
            Statistic        Value            Value
Value
------------------------------------------------------------------------
 Z(t)         -1.071          -3.750          -3.000          -2.630
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.7263
```

South Africa

```
Dickey-Fuller test for unit root                Number of obs   =       28

                         ---------- Interpolated Dickey-Fuller ---------
              Test        1% Critical      5% Critical     10% Critical
            Statistic        Value            Value
Value
------------------------------------------------------------------------
 Z(t)          0.586          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9873
```

Spain

```
Dickey-Fuller test for unit root                Number of obs   =       28

                         ---------- Interpolated Dickey-Fuller ---------
              Test        1% Critical      5% Critical     10% Critical
            Statistic        Value            Value
Value
------------------------------------------------------------------------
 Z(t)         -1.889          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.3372
```

Sweden

```
Dickey-Fuller test for unit root              Number of obs   =       28

                  ---------- Interpolated Dickey-Fuller ---------
          Test       1% Critical      5% Critical     10% Critical
        Statistic        Value           Value
Value
------------------------------------------------------------------------------
 Z(t)         -1.038          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.7390
```

Switzerland

```
Dickey-Fuller test for unit root              Number of obs   =       28

                  ---------- Interpolated Dickey-Fuller ---------
          Test       1% Critical      5% Critical     10% Critical
        Statistic        Value           Value
Value
------------------------------------------------------------------------------
 Z(t)         -0.303          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9251
```

Turkey

```
Dickey-Fuller test for unit root              Number of obs   =       28

                  ---------- Interpolated Dickey-Fuller ---------
          Test       1% Critical      5% Critical     10% Critical
        Statistic        Value           Value
Value
------------------------------------------------------------------------------
 Z(t)         -1.309          -3.730          -2.992          -2.626
------------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.6252
```

United Kingdom

```
Dickey-Fuller test for unit root                Number of obs   =       28

                     ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical      5% Critical     10% Critical
           Statistic        Value           Value
Value
------------------------------------------------------------------------
 Z(t)          0.718          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9902
```

United States

```
Dickey-Fuller test for unit root                Number of obs   =       28

                     ---------- Interpolated Dickey-Fuller ---------
             Test       1% Critical      5% Critical     10% Critical
           Statistic        Value           Value
Value
------------------------------------------------------------------------
 Z(t)          0.901          -3.730          -2.992          -2.626
------------------------------------------------------------------------
MacKinnon approximate p-value for Z(t) = 0.9931
```

Augmented Dickey–Fuller Test for the First Difference of log MP

Australia

```
Dickey-Fuller test for unit root                 Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value            Value            Value

Z(t)          -8.877          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Austria

```
Dickey-Fuller test for unit root                 Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value            Value            Value


Z(t)          -4.462          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0002
```

Belgium Luxembourg

```
Dickey-Fuller test for unit root                  Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value            Value            Value


Z(t)          -6.250          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Brazil

```
Dickey-Fuller test for unit root                 Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value            Value            Value


Z(t)          -6.023          -3.736          -2.994          -2.628
MacKinnon approximate p-value for Z(t) = 0.0000
```

Canada

```
Dickey-Fuller test for unit root                Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value           Value           Value

Z(t)           -6.732          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Chile

```
Dickey-Fuller test for unit root                 Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value           Value           Value


Z(t)           -3.697          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0042
```

China

```
Dickey-Fuller test for unit root                Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value           Value           Value

Z(t)           -3.193          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0204
```

Czech Republic

```
Dickey-Fuller test for unit root                Number of obs   =       14

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value           Value           Value


Z(t)           -4.551          -3.750          -3.000          -2.630

MacKinnon approximate p-value for Z(t) = 0.0002
```

Denmark

```
Dickey-Fuller test for unit root              Number of obs   =      27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic        Value            Value           Value

Z(t)          -6.438          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Estonia

```
Dickey-Fuller test for unit root              Number of obs   =      12

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic        Value            Value           Value
Z(t)          -3.337          -3.750          -3.000          -2.630

MacKinnon approximate p-value for Z(t) = 0.0133
```

Finland

```
Dickey-Fuller test for unit root              Number of obs   =      27

----------  Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic        Value            Value           Value

Z(t)          -7.844          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

France

```
Dickey-Fuller testfor unit root              Number of obs   =      27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic        Value            Value           Value

Z(t)          -6.231          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Germany

```
Dickey-Fuller test for unit root              Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical      5% Critical     10% Critical
Statistic         Value           Value           Value
Z(t)          -4.541          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0002
```

Greece

```
Dickey-Fuller test for unit root              Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical      5% Critical     10% Critical
Statistic         Value           Value           Value

Z(t)          -6.156          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Hungary

```
Dickey-Fuller test for unit root              Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical      5% Critical     10% Critical
Statistic         Value           Value           Value

Z(t)          -5.291          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Iceland

```
Dickey-Fuller test for unit root              Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical      5% Critical     10% Critical
Statistic         Value           Value           Value

Z(t)          -5.456          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

India

```
Dickey-Fuller test for unit root              Number of obs   =      27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic       Value           Value           Value

Z(t)          -4.481         -3.736         -2.994         -2.628

MacKinnon approximate p-value for Z(t) = 0.0002
```

Ireland

```
Dickey-Fuller test for unit root              Number of obs   =       7

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic       Value           Value           Value

Z(t)          -2.902         -3.750         -3.000         -2.630

MacKinnon approximate p-value for Z(t) = 0.0451
```

Israel

```
Dickey-Fuller test for unit root              Number of obs   =      27

---------- InterpolatedDickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic       Value           Value           Value

Z(t)          -4.485         -3.736         -2.994         -2.628

MacKinnon approximate p-value for Z(t) = 0.0002
```

Italy

```
Dickey-Fuller test for unit root              Number of obs   =      27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic       Value           Value           Value

Z(t)          -3.401         -3.736         -2.994         -2.628

MacKinnon approximate p-value for Z(t) = 0.0109
```

Japan

```
Dickey-Fuller test for unit root                Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical      10% Critical
Statistic         Value            Value             Value

Z(t)          -5.837          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Korea, Republic of

```
Dickey-Fuller test for unit root                Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical      10% Critical
Statistic         Value            Value             Value

Z(t)          -4.591          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0001
```

Mexico

```
Dickey-Fuller test for unit root                Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical      10% Critical
Statistic         Value            Value             Value

Z(t)          -6.767          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Netherlands

```
Dickey-Fuller test for unit root                Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical      10% Critical
Statistic         Value            Value             Value

Z(t)          -7.268          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

New Zealand

```
Dickey-Fuller test for unit root              Number of obs   =      27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic        Value           Value           Value

Z(t)         -7.052          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Norway

```
Dickey-Fuller test for unit root              Number of obs   =      27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic        Value           Value           Value

Z(t)         -5.420          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Poland

```
Dickey-Fuller test for unit root              Number of obs   =      17

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic        Value           Value           Value

Z(t)         -6.698          -3.750          -3.000          -2.630

MacKinnon approximate p-value for Z(t) = 0.0000
```

Portugal

```
Dickey-Fuller test for unit root              Number of obs   =      27

----------Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic        Value           Value           Value

Z(t)         -6.524          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Russian Federation

```
Dickey-Fuller test for unit root              Number of obs  =      15

---------- Interpolated Dickey-Fuller ---------

Test        1% Critical      5% Critical     10% Critical
Statistic         Value            Value            Value

Z(t)          -5.140          -3.750          -3.000          -2.630

MacKinnon approximate p-value for Z(t) = 0.0000
```

Slovak Republic

```
Dickey-Fuller test for unit root              Number of obs  =      14

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value            Value            Value

Z(t)          -2.936          -3.750          -3.000          -2.630

MacKinnon approximate p-value for Z(t) = 0.0413
```

Slovenia

```
Dickey-Fuller test for unit root              Number of obs  =      15

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value            Value            Value

Z(t)          -4.052          -3.750          -3.000          -2.630

MacKinnon approximate p-value for Z(t) = 0.0012
```

South Africa

```
Dickey-Fuller test for unit root              Number of obs  =      27

---------- Interpolated Dickey-Fuller ---------
Test        1% Critical      5% Critical     10% Critical
Statistic         Value            Value            Value

Z(t)          -5.156          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Spain

```
Dickey-Fuller test for unit root              Number of obs   =     27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic        Value           Value           Value

Z(t)        -5.962        -3.736        -2.994        -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Sweden

```
Dickey-Fuller test for unit root              Number of obs   =     27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic        Value           Value           Value

Z(t)        -8.337        -3.736        -2.994        -2.628

MacKinnon approximate p-value for Z(t) = 0.0000
```

Switzerland

```
Dickey-Fuller test for unit root              Number of obs   =     27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic        Value           Value           Value

Z(t)        -2.920        -3.736        -2.994        -2.628

MacKinnon approximate p-value for Z(t) = 0.0430
```

Turkey

```
Dickey-Fuller test for unit root              Number of obs   =     27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical     5% Critical     10% Critical
Statistic        Value           Value           Value

Z(t)        -4.650        -3.736        -2.994        -2.628

MacKinnon approximate p-value for Z(t) = 0.0001
```

United Kingdom

```
Dickey-Fuller test for unit root              Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical      5% Critical      10% Critical
Statistic        Value            Value             Value

Z(t)        -4.200          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0007
```

United States

```
Dickey-Fuller test for unit root              Number of obs   =       27

---------- Interpolated Dickey-Fuller ---------
Test       1% Critical      5% Critical      10% Critical
Statistic        Value            Value             Value

Z(t)        -4.665          -3.736          -2.994          -2.628

MacKinnon approximate p-value for Z(t) = 0.0001
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Databases

Data on material flows obtained from http://www.materialflows.net. Global Materialflow Database. Data download on August 31, 2012.

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