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GLOBAL MATERIAL FLOWS AND RESOURCE PRODUCTIVITY

Assessment Report for the UNEP International Resource Panel

UNITED NATIONS ENVIRONMENT PROGRAMME

Acknowledgements

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Preface

Janez Potočnik

Alicia Bárcena

In recent years, interest in resource efficiency and sustainable management of natural resources has increased considerably, standing out as one of the top priorities on the international political agenda.

With the historic adoption of the 2030 Agenda for Sustainable Development in September 2015 in New York, the international community committed itself to 17 Sustainable Development Goals to transform our world into a better place for current and future generations. It has been widely acknowledged that such a world can only be achieved and sustained if we better take care of, conserve and use natural resources and significantly improve resource efficiency in both consumption and production in the years to come. The SDGs emphasize the pressing need to decouple economic growth and human well-being from ever-increasing use of natural resources and related environmental impact.

As part of this historic recognition, the leaders of the G7, at their summit in Germany in 2015, decided to champion ambitious actions to improve resource efficiency as a core element of a broader strategy in pursuit of sustainable development.

All around the world, strategies and programmes that are mainstreaming sustainable natural resource management into national development plans are being designed and implemented. A growing number of countries are promulgating laws and regulations and implementing effective policy frameworks that support resource efficiency and guide investments into green and greening sectors of the economy.

Accurate, reliable data and scientific information are essential to economic planning and policymaking. Robust indicators are needed to measure progress with decoupling and resource efficiency and identify areas for improvement.

The International Resource Panel has produced several scientific assessment reports on resource efficiency and decoupling and is therefore in the perfect position to provide precisely such scientifically profound, policy-relevant information.

With this report, the Working Group on Global Material Flows of the International Resource Panel provides, for the first time, a comprehensive and harmonized data set of material use and movement in the global economy for the past 40 years. Based on this solid data set, it analyses status, trends, structure and dynamics of resource use, including extraction, trade and consumption of biomass, fossil fuels, metal ores and non-metallic minerals. The report finds that global material use has tripled over the past four decades, with annual global extraction of materials growing from 22 billion tonnes (1970) to 70 billion tonnes (2010).

The report also provides a new material footprint indicator, reporting the amount of materials that are required for final consumption, which sheds light on the true impact of economies. By relating global supply chains to final demand for resources, the indicator is a good proxy for the average material standard of living in a country. It indicates that the level of development and well-being in wealthy industrial countries has been achieved largely through highly resource-intensive patterns of consumption and production, which are not sustainable, even less replicable to other parts of the world.

Hence, decoupling material use and related environmental impacts from economic growth is essential for ensuring the prosperity of human society and a healthy natural environment. But in order to be successful, decoupling efforts need to go beyond simple efficiency gains that arise from maturing economies.

This report also shows that consumption is the main driver of increased material use, more important than population growth in recent decades. With millions of people lifted out of poverty and a rapidly expanding middle class in the coming decades, a prosperous and equitable world calls for transformative changes in lifestyles and consumption behaviour.

The findings of this report have the potential to contribute significantly to many national and regional natural resource management and resource efficiency efforts and are particularly relevant for the implementation and monitoring of all decoupling-related Sustainable Development Goals over the next 14 years.

The International Resource Panel is committed to continuing to provide cutting-edge scientific knowledge on sustainable resource management and resource efficiency. We are very grateful to Heinz Schandl and Marina Fischer-Kowalski and their co-authors for their important contribution to the understanding of global material flows and resource productivity, and we are very much looking forward to the response of policy-makers and business leaders to the tremendous challenges, opportunities and implications highlighted in this report and data set.

Foreword

Ibrahim Thiaw

Natural resources provide the foundation of our lives on Earth. Water, soil, energy, minerals and metals underpin our standards of living. They feed and shelter us, and provide for our material needs throughout our lives.

Yet pressures on these natural resources are mounting. A growing population and heightened world economic demand in the past half century are rapidly depleting these vital resources, inflicting great harm on the natural environment and human health. In our ever-more globalized economy, sustainable management of natural resources will become increasingly important.

When the world's nations approved the Sustainable Development Goals in 2015, they set out a path towards solving some of these great challenges. These ambitious goals aim to eradicate poverty and sustain economic growth, while maintaining the natural resource base and planetary ecosystems for future generations. Turning the goals into reality will require concerted action by the entire world, developed and developing countries alike. For these reasons, we must better understand where and how natural resources are used.

This latest report from the International Resource Panel, Global Material Flows and Resource Productivity, provides a comprehensive, scientific overview of this important issue. It shows a great disparity of material consumption per capita between developing and developed countries. This has tremendous implications for achieving the SDGs in the next 14 years.

Global material use has been accelerating. Material extraction per capita increased from 7 to 10 tonnes from 1970 to 2010, indicating improvements in the material standard of living in many parts of the world. Domestic extraction of materials has grown everywhere to meet increased demand for materials. However, Europe and the Asia-Pacific region have not met all of their material demand from domestic extraction and have increasingly relied on large imports. Trade in materials is thus booming, driven mainly by consumption.

The report also lays bare the large gaps in material standards of living that exist between North America and Europe and all other world regions. Annual per capita material footprint for the Asia-Pacific, Latin America and the Caribbean, and West Asia is between 9 and 10 tonnes, or half that of

Europe and North America, which is about 20 to 25 tonnes per person. In contrast, Africa has an average material footprint of below 3 tonnes per capita. Such a distribution of materials supports unequal standards of living and highlights how much work will be needed to achieve sustainable development for all.

It is my sincere hope that the findings of this important assessment will inspire political and business leaders to take the action needed to achieve the SDGs.

I would like to express my gratitude to the International Resource Panel, under the leadership of Janez Potočnik and Alicia Bárcena, for developing this substantial report.

Ibrahim Thiaw
United Nations Assistant-Secretary-General
and UNEP Deputy Executive Director

Abbreviations

AMI	adjusted material intensity
BRIC	Brazil, Russia, India, China
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
DE	domestic extraction
DMC	domestic material consumption
EEA	European Environmental Agency
EECCA	Eastern Europe, Caucasus and Central Asia
EF	energy footprint
EROEI	energy return on energy invested
ETM	elaborately transformed manufactures
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
GFC	global financial crisis
GHG	greenhouse gas
GHGF	GHG emissions footprint
GHGI	GHG intensity
HDI	human development index
IEA	International Energy Agency
IMF	International Monetary Fund
IPAT	I = P x A x T equation
IRP	International Resource Panel of the United Nations Environment Programme
MF	material flows
MI	material intensity
MJ	megajoules
MRIO	multi-regional input-output
n.e.c.	not elsewhere classified
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PJ	petajoules
PTB	physical trade balance
RME	raw material equivalents
RTB	raw material trade balance
SCP	sustainable consumption and production
SEEA	System of Environmental-Economic Accounting
TJ	terajoules
TPES	total primary energy supply
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization

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Executive summary

Resource efficiency now high on the global policy agenda

This initiative of the Group of 7 resonates well with the United Nations agenda and the new 2030 Agenda for Sustainable Development and its 17 SDGs, which see sustainable natural resource use as a condition of achieving the developmental outcomes for nations outlined in the SDGs. Sustainable consumption and production (SCP), resource efficiency and waste minimization (the 3Rs – reduce, reuse, recycle) are featured both as stand-alone goals and integrated into the targets of other SDG goals. The need to decouple economic growth and human well-being from ever-increasing consumption of natural resources is now very evident in the policy community and many countries have initiated policies to facilitate decoupling.

Measuring economic activity at aggregate and detailed levels through the System of National Accounts is a standard activity undertaken by every country. This study by the UNEP International Resource Panel provides, for the first time, a coherent account of material use in the global economy and every nation which is complementary to the System of National Accounts. The study reports material extraction and trade of materials to provide an authoritative database and indicators that can be used by the policy community to monitor progress of resource efficiency policies. The data are made available online and the purpose of this report is to discuss the major global and regional trends in material use and resource productivity.

Global natural resource use has accelerated

Growth of global material use has accelerated over the past four decades, while economic growth and population growth have been slowing. Overall, the global economy expanded more than threefold over the four decades since 1970, population almost doubled and global material extraction tripled. The world economy has experienced a great acceleration in material use since 2000, strongly related to the industrial and urban transformation in China, which has required unprecedented amounts of iron and steel, cement, energy and construction materials. China's growth in material demand since the year 2000 has reverberated across the world economy, especially in primary resource exporting regions and countries such as Latin America, Africa and Australia.

The study also demonstrates the close relationship between economic trends and natural resource use. Global material use slowed in 2008 and 2009 due to the global financial crisis, with trade flows contracting in 2009, but is again on a growth trajectory. Sustained reductions in material use depend on changes in the structural asset base of an economy. This means that there is considerable inertia built into the global system of material use, which makes it difficult to reduce material use rapidly and on a sustained basis.

Growth in global material extraction was such that per capita global material use increased from 7 tonnes per capita in 1970 to 10 tonnes per capita in 2010, indicating improvements in the material standard of living in many parts of the world. Domestic extraction of materials has grown in all world regions to meet increased demand for materials. The densely populated global regions of Europe and Asia and the Pacific have not been meeting all of their material demand from domestic extraction of natural resources, despite large increases in agricultural production and mining in Asia and the Pacific region, especially. These two regions have required large and increasing amounts of imports of materials, especially fossil fuels and metal ores, from all other regions.

Trade in materials has grown dramatically

As a result, trade has grown faster than domestic extraction and direct trade in materials has expanded fourfold since 1970. In 2010, more than 10 billion tonnes of materials were exported globally. In this report we also account for the raw material equivalents of direct trade of materials. The new indicators of raw material equivalent of imports and exports show that trade mobilizes much greater amounts of materials than direct traded flows indicate. In 2010, 30 billion tonnes of materials extracted globally were required to produce 10 billion tonnes of directly traded goods. A raw material trade balance based on the attribution of globally extracted materials to traded goods shows that only Europe and North America have remained net importers of materials. By contrast, the Asia-Pacific region has changed into a net exporter of materials through large exports of manufactured goods which are mostly consumed in Europe and North America.

Over the four decades an increasing specialization of countries with regard to natural resource extraction for trade has emerged, especially for fossil fuels and metal ores but to some extent also for agricultural products. This is especially visible at the country level where countries such as Australia, Brazil, Chile, Indonesia and Kazakhstan have increased their net exports of materials over time while other countries such as South Korea and the United States (until 2005) increased their net imports of materials, or depended (such as Germany, France and Japan) on a high level of net imports over the four decades. China, India and Pakistan show an interesting pattern of fast increasing import dependency for the direct trade of materials which coincides with the status of a net exporter when adjusting trade flows for upstream and downstream indirect material flows associated with trade, i.e. looking at the raw material equivalents of trade.

This increasing specialization has also created very different environmental and social issues in countries which are net exporters or net importers of materials. It also creates a different policy context for sustainable natural resource use and decoupling of economic growth from material use. Importing countries have strong incentives to invest in material efficiency – achieving more with less – strategies and policies, which are not matched by exporting countries. Both types of countries are affected by global resource price changes but in very different ways. Countries relying on material imports profit from low world market prices and their economic performance is harmed by high prices. Material exporters make windfall gains when natural resource prices are high but experience a hit to their balance of trade when prices fall and production contracts; these effects have been experienced in recent months in commodity exporting regions such as Latin America.

Consumption has been driving material use

Globally, growth in per capita income and consumption has been the strongest driver of growth in material use, even more important than population growth in recent decades, especially since 2000. Population has continued to contribute to rising material demand but not to the same extent as rising per capita income and the emergence of a new middle class in developing countries. Material efficiency mitigated some of the growth of material use driven by growing population and world economy between 1970 and 1990. Since 1990, there has not been much improvement in global material efficiency, which actually started to decline around 2000.

The material intensity of the global economy has increased

The material intensity of the world economy has been increasing for the past decade, driven by the great acceleration that has occurred since the year 2000. Globally, more material per unit of GDP is now required. Production has shifted from very material-efficient countries to countries that have low material efficiency, resulting in an overall decline in material efficiency. Countries earn a material efficiency dividend as their economies mature and most countries of the world have improved their material productivity over time, i.e. they use less material per unit of GDP. Most countries have followed this path over the past four decades with the exception of a number of resource-exporting countries whose material intensity has been stable. Despite this, global material productivity has declined since about the year 2000 and the global economy now needs more materials per unit of GDP than it did at the turn of the century. What may seem counter-intuitive has been caused by a large shift of economic activity from very material-efficient economies such as Japan, the Republic of Korea and Europe to the much less material-efficient economies of China, India and Southeast Asia.

This has resulted in growing environmental pressure per unit of economic activity and works against the hypothesis of decoupling – achieving more with less – which is so important to the success of global sustainability. Additional effort around public policy and financing will be required to improve the efficiency of material use substantially over the coming decades.

A new indicator, material footprint of consumption, shows the true impact of wealthy economies on global material use

This report adopts a new indicator for the material footprint of consumption, which reports the amounts of materials that are required for final demand (consumption and capital investment) in a country or region. This indicator is a good proxy for the material standard of living. The current global systems of production result in a material footprint of Europe's consumption of around 20 tonnes per capita and a material footprint of North America's consumption of around 25 tonnes per capita. Both regions have experienced a decline in material footprint since 2008 caused by the economic downturn during the global financial crisis (GFC). Before the GFC, North America had a per capita material footprint of well above 30 tonnes and Europe of well above 20 tonnes and both regions were on an upward trajectory. It remains to be seen whether the economic recovery in North America and Europe has put material footprint on a growth trajectory again. This would suggest that there is no level of income yet at which material use has stabilized.

The material footprint indicator allows, differently from measures of material extraction and direct material use, the establishment of a landing point for industrial material use. It may well be that industrial metabolism stabilizes at between 20 and 30 tonnes per capita for the current ways in which we build houses and transport infrastructure, how we organize mobility, and deliver manufactured goods, food and energy. Given the fact that the global economy, at today's level of resource use, is already surpassing some environmental thresholds or planetary boundaries, this shows that the level of well-being achieved in wealthy industrial countries cannot be generalized globally based on the same system of production and consumption. Large improvements in decoupling are needed to service the needs and aspirations of a growing global population in an inclusive way.

Large gaps in material standard of living persist

There is still a large gap in the average material standard of living and resulting material footprint between North America and Europe and all other world regions. Annual per capita material footprint for Asia and the Pacific, Latin America and the Caribbean and West Asia is between 9 and 10 tonnes, or half the per capita material footprint of Europe. The EECCA region is following with 7.5 tonnes per capita and Africa, on average, has a material footprint of below 3 tonnes per capita. These results are confirmed when we look at the relationship between human development and material footprint, where very high human development as measured by the human development index (HDI) required around 25 tonnes of material footprint and was rising before the GFC. The group of countries of high human development have experienced the fastest growth in material footprint and are now, on average, at 12.5 tonnes per capita, up from 5 tonnes per capita in 1990. China, for instance, had a material footprint of 14 tonnes per capita in 2010 on a strong upward trajectory and Brazil had a material footprint of 13 tonnes per capita in 2010 and has also grown strongly in recent years.

The average material footprint of countries with medium levels of human development has grown slowly over the past two decades, reaching 5 tonnes per capita, while material footprint in low HDI countries has been stagnant for the past two decades at 2.5 tonnes per capita. The richest countries consume on average 10 times as many materials as the poorest countries, and twice the world average, which demonstrates very unequal distribution of materials to support the standard of living. It shows that the low income group of countries will require increasing quantities of materials, per capita, to achieve the sustainable development outcomes the global community aims for.

A comprehensive database for global material flows

This report provides a comprehensive understanding of linkages between the world economy, population and material use over four decades (1970–2010) based on a new and authoritative database of global material extraction and a revised database for materials trade. It uses a standard set of material flow accounting indicators as well as new indicators. The data and indicators presented in this report will allow countries and regions to monitor their progress in achieving greater material efficiency through well-designed national policies and regional initiatives. We present a large data set covering 40 years (1970–2010) and most countries of the world. We present direct and consumption-based material flow indicators for seven world regions and for individual countries, covering total usage, per capita use and per US$. We also provide detail for different groups of materials and relate indicators to human development outcomes.

The report also provides similar information for each of seven world regions and about 180 countries to support informed decision-making by the policy and business communities. The outlook is for further growth in material use if countries successfully improve economic and human development, and are able to raise living standards and combat poverty. Assuming that the world will implement similar systems of production and systems of provision for major services – housing, mobility, food, energy and water supply – nine billion people will require 180 billion tonnes of materials by 2050, almost three times today's amounts.

In this report, the use of materials – society's metabolism – is interpreted as an environmental pressure. The larger the material use the bigger the pressure. Material use is also closely related to other pressure indicators including waste flows, energy use and carbon emissions, land use and water use. When material use grows, ceteris paribus also the other pressure indicators will increase. Material use is also used as a proxy for environmental impacts that will occur across the whole life cycle of material use from extraction, transformation and consumption to disposal. When material use increases, the environmental, social and economic impacts of material use also see a commensurate rise. Rising material use will result in climate change, higher levels of acidification and eutrophication of soils and water bodies, increased biodiversity loss, more soil erosion and increasing amounts of waste and air pollution. It will also have negative impacts on human health and quality of life. It will ultimately lead to the depletion of certain natural resources and will cause supply shortages for critical materials in the short and medium terms.

While many resources will still be abundantly available over the medium and long terms, pollution and ecosystem degradation and a changing climate will dominate the political debate around using materials more effectively and efficiently. Fast-expanding demand for materials will, however, require very large investments into new extraction and supply infrastructure and will contribute to local conflict over alternative uses of land, water, energy and materials. Such conflict is already pronounced in the energy sector where mining competes with agriculture and urban development in many places.

Decoupling is the imperative of modern environmental policy

Decoupling of material use and related environmental impacts from economic growth is a strategy that will be instrumental for ensuring future human well-being based on much lower material throughput. Many regions and countries have embarked on a strategy to substantially increase the material efficiency of their economies and to reduce the overall level of material use. Many countries and regions, including the European Union, Japan and China among others, now have high-level policy frameworks and laws that support resource efficiency and guide investments into green sectors of the economy supported by sustainable consumption and production practices. UNEP and the IRP aim to provide information that supports policy formulation in the domain of resource efficiency and waste minimization and allows countries to monitor progress of their efforts to reduce material throughput and improve the material efficiency of their economies.

CHAPTER

1

Introduction

Introduction

Our world is built from materials. The food we eat, the buildings that house us, the vehicles in which we travel and the consumer goods that furnish our life, are all made of, embody and require for their operation massive quantities of biomass, fossil fuels, metals and non-metallic minerals. Materials fuel our economies and underpin human development and well-being. Our dependence on materials links us directly to the natural world from which primary materials are extracted, and to which they all ultimately return as waste and emissions. This notion of a physical economy that underpins production and consumption systems is captured by the concepts of social metabolism (Fischer-Kowalski 1997) and industrial metabolism (Ayres and Simonis 1994).

The primary sectors of the economy (agriculture, forestry, fishing, mining and quarrying) extract materials from the natural resource base and turn them into the basic commodities required for various major economic activities. Access to abundant and affordable materials is critical for the economic success of a national economy and fundamental to the ongoing well-being of its citizens. During the twentieth century, the economic development that improved material standards of living for hundreds of millions of people was assisted by declining real prices for most materials, including food, fuel and metals. This situation may not be sustained through the twenty-first century as the rapid economic growth occurring simultaneously in many parts of the world will place much higher demands on supply infrastructure and the environment's ability to continue supplying materials. The most notable example of such rapid and resource intensive growth is China (Schandl and West 2012), however rapidly increasing demand for primary materials is also seen in various Southeast Asian nations, India, Brazil and Nigeria, to name a few.

This assessment report quantifies the ever-increasing material flows required to build, maintain and operate the cities, transport systems, food supply and energy systems on which today's world depends. The importance of understanding these flows is twofold. There are very important environmental impacts related to the mobilization of materials for use in economic activity. Large-scale change in land use and forest cover accompanies the extension of agriculture, timber production and in some cases mining and energy extraction. Impacts associated with increasing agricultural outputs include large-scale land degradation via erosion, salinization and acidification which can accompany the extension of cropping into marginal lands or the intensification of inputs on existing arable land.

Further problems include the destruction of biodiversity and the eutrophication of waterways. Increasing outputs of forestry products can increase deforestation, with attendant damage to surface and groundwater systems, erosion and changed flooding regimes. Problems associated with mining and quarrying include loss of land to competing land uses, pollution of land and waterways from acid mine leaching, heavy metals liberated from mine tailings, and some chemicals used in mining and refining processes. Secondary and tertiary production processes, and disposal after final consumption, add to waste and emissions downstream. Ultimately, everything that is extracted must be sunk back into the environment in some form, after sufficient time.

In a world where climate change, food security and supply security of strategic resources have converged rapidly there is an imperative to focus on resource efficiency and decoupling: the need to achieve more using less.

1.1 The purpose of this assessment study

Over the past decade, and in response to the acceleration of material use in the global economy, many countries now require reliable information about material use in their economies. The European Union uses indicators for material use and material efficiency (resource productivity) for its resource efficiency roadmap, which is one of the building blocks of Europe's resource efficiency flagship initiative and part of the Europe 2020 strategy. EU Member countries report material flow data biannually to the European Statistical Office (Eurostat) which compiles Europe's material flow data and makes the data accessible through its website. The Organisation for Economic Co-operation and Development (OECD) has adopted a resource productivity indicator as part of its Green Growth strategy. The Japanese Government uses a material intensity indicator to monitor progress of the Sound Material Cycle Society high-level policy goal (Takiguchi and Takemoto 2008).

The United Nations Environment Programme (UNEP) has used material flow indicators for regional reports for Asia and the Pacific, Latin America and the Caribbean, and Eastern Europe, Central Asia and the Caucasus regions. The United Nations Industrial Development Organization (UNIDO) has supported the study of material flows for Africa. Demand for material flow data and indicators has grown globally and the assessment study and associated data set made available publicly at the UNEP Live online data platform respond to this demand.

For this assessment study, we reviewed the existing global databases and compared their methodological underpinnings and results in an effort to create one unified data set that can become the standard authoritative source for data on global and country by country material use. In doing so, we were able to establish a multi-country, global data set for year by year material extraction for the four decades from 1970 to 2010 including information for all countries of the world as far as possible. The materials extraction data set reports 44 different material categories and includes a series of data refinements that have occurred in the process of aligning and choosing between the different source data sets. The derivation of the final database, and the underlying source data sets, are described in detail in the technical annex. We also present a revised data set for trade flows based on a more comprehensive coverage and aggregation of trade data. For the first time, we present a data set for material footprints of consumption using a methodology that has been introduced recently (Wiedmann et al. 2015b) and is based on the most detailed and comprehensive global, multi-regional input-output framework available to date.

For domestic extraction we focus on those materials that enter the economic process and become commodified (used extraction) but do not account for materials that are mobilized but do not enter the economy (unused extraction). Unused extraction can be a very large material flow but is much harder to measure compared to used extraction and has higher data uncertainty. It is also less related to national accounts and is hence excluded in this assessment study.

Based on the data set we report a set of material flow indicators for the global level (Chapter 2) and the seven UNEP regions (chapters 3 and 4). We focus on drivers of material use in Chapter 5 and the relationship between human development and material use in Chapter 4. The indicators presented include:

- Domestic extraction of materials (DE)
- Imports of materials (Imports)
- Direct material input (DMI)
- Export of materials (Exports)
- Physical trade balance (PTB)
- Domestic material consumption (DMC)
- Raw material equivalents of imports ($RME_{Imports}$)
- Raw material equivalents of exports ($RME_{Exports}$)
- Raw material trade balance (RTB)
- Material footprint of consumption (MF) / Raw material consumption (RMC)

Table 1. Indicators covered in this report

Indicator name	Meaning of indicator	Disaggregation
Domestic extraction of materials (DE)	Domestic extractive pressure on natural resources	44 material categories
Imports of materials (Imports)	Direct imports	11 material categories
Domestic material input (DMI), i.e. DE plus Imports	Material requirement of production	11 material categories
Export of materials (Exports)	Direct exports	11 material categories
Physical trade balance (PTB), i.e. Imports minus Exports	Direct trade dependency	11 material categories
Domestic material consumption (DMC), i.e. DE plus PTB	Long-term waste potential	11 material categories
Raw material equivalents of imports ($RME_{Imports}$)	Upstream material requirements of imports	4 material categories
Raw material equivalents of exports ($RME_{Exports}$)	Upstream material requirements of exports	4 material categories
Raw material trade balance (RTB), i.e. $RME_{Imports}$ minus $RME_{Exports}$	Trade dependency of consumption	4 material categories
Material footprint of consumption (MF), Raw material consumption (RMC), i.e. DE plus RTB[1]	Global extractive pressure on natural resources of consumption	4 material categories
Material intensity (MI), i.e. DMC per US$	Efficiency of material use	1 category
Adjusted material intensity (AMI), i.e. MF per US$	Efficiency of material use corrected for trade	1 category

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[1] MF and RMC are identical measures of the raw material requirement of final demand of a country. Both terms are used in the peer-reviewed literature. The first refers to the conceptual relationship with other footprint accounts for energy, carbon emissions and water, the latter relates to the conceptual language of material flow accounting.

1.2 Accounting for global material use

To monitor progress of the decoupling of economic activity from material use, accounts of material flows are required. Compiling these accounts at global, regional and national levels enables better planning and decision-making at different scales. Not surprisingly, efforts to account for national material use have a long history in major economies, including the United States and the Soviet Union. Both established accounts of their natural resource base and the material requirements of the economy, and the supply systems required to deliver those resources. The most prominent early example is the Paley report (Paley 1952), which assessed the resource base of the United States and its trading partners, and compared it to that available to the Soviet Union and its economic allies. Attempts to measure global material use are, however, more recent.

Two ground-breaking studies led by the World Resources Institute (Adriaanse et al. 1997, Matthews et al. 2000) compared material and waste flows for a number of national economies, within a comprehensive material balance framework, triggering a process of methodological harmonization. Eurostat has operated a task force for methods harmonization since 2003, and has published a series of guidebooks for national material flow accounts (Eurostat 2001, Eurostat 2009, Eurostat 2013).

Eurostat works closely with the OECD, which also promotes data and indicators for material flows and resource productivity, implementing a 2003 decision of the Group of Eight (G8) countries spearheaded by the Japanese Government. The OECD approach to material flow accounting has also resulted in a number of important reports focusing on the policy implications of such reporting.

Material flow accounting aims for complementarity with the System of National Accounts and hence it was a logical step to integrate MFA into the System of Environmental-Economic Accounting (SEEA) framework during the last revision of the SEEA (United Nations 2014).

Two independent studies (Schandl and Eisenmenger 2006, Behrens et al. 2007) provided measures of global material use for the first time, and came up with very similar levels of global material use at the turn of the last century. These studies raised awareness of the sheer magnitude of material use that has fuelled socioeconomic development at the global scale. The first study reported global and regional material flows for the year 1999 and the latter presented time series for 1980 to 2002. The global perspective has been accompanied by a series of studies that have focused on different world regions which include Europe (Weisz et al. 2006), Asia and the Pacific (Schandl and West 2010, Schandl and West 2012), Latin America and the Caribbean (West and Schandl 2013) and Eastern Europe, Caucasus and Central Asia (West et al. 2014).

The growing number of regional and global studies have increasingly employed very similar methodologies and base data sources, and have also resulted in a number of global data sets being made available online. These include the global material flow database of the Vienna University of Economics and Business (WU), the CSIRO global material flows database, and the database hosted by the Institute of Social Ecology in Vienna. The first two data sets have formed the basis for a number of global and regional reports among which *Green Economies around the World? Implications of Resource Use for Development and the Environment* (Dittrich et al. 2012b) and Resource Efficiency: Economics and Outlook for Asia and the Pacific (UNEP 2011b) figure prominently. Other studies with the available global data sets include (Giljum et al. 2014, Krausmann et al. 2009, Steinberger, Krausmann and Eisenmenger 2010, Steinberger et al. 2013).

A recent review article found that the large research effort by a number of international research institutes meant that global data sets have recently cohered to a high degree (Fischer-Kowalski et al. 2011).

In recent decades trade in materials has grown both in quantity and in relative importance (Dittrich and Bringezu 2010). Most recently, the latest trends in trade have been summarized in UNEP (2015). The growing complexity of international supply chains, driven by globalization of the world economy, has paired with a trend whereby high-income countries tend to outsource many materials-, energy- and emissions-intensive industrial processes to other parts of the world. The high-income country can then effectively import the primary commodities it needs either in a greatly concentrated form, or indirectly "embodied" in a relatively small quantity of imports. The conventional measures used in material flows accounting are largely blind to such extraterritorial inputs to a nation's final demand. This created a need for a new indicator that captures the full material requirements of a country's final demand (household and government consumption, and capital investment), which includes extraterritorial inputs of materials for local consumption.

While accounting for the indirect flows of materials embodied in trade is a less mature field compared to direct accounting, a number of recent studies have demonstrated the feasibility of such an approach (Wiedmann et al. 2015a, Giljum, Bruckner and Martinez 2015). The research community is increasingly turning to multi-regional, global input-output (MRIO) frameworks when seeking to attribute global materials extraction to the country of final demand. Current results from different frameworks still diverge, in part because of different sectoral and geographical detail expressed in the various models, so considerable research effort is being focused on investigating the main differences between the most comprehensive current MRIO frameworks. A number of global studies are now available that have measured the raw material equivalents of trade, and a new indicator, the material footprint of consumption, has been proposed (Wiedmann et al. 2015a). There are also alternatives to the MRIO approach for the attribution of global resource use to final demand, including those based on application of life cycle analysis factors to direct trade flows (Dittrich, Bringezu and Schütz 2012a) and hybrid approaches (Schoer et al. 2012, Schaffartzik et al. 2014).

1.3 Historical variability in the world economy

The past four decades have been characterized by fast growth in population, almost doubling from 3.7 billion people in 1970 to 6.9 billion people in 2010, an average annual growth rate of 1.6% compounding. The global economy has grown much faster than population, increasing from 15.7 trillion dollars in 1970 to 52.9 trillion dollars (real 2005 prices) in 2010, an average annual growth rate of 3.1%. By 2013, global gross domestic product (GDP) was at 56.8 trillion dollars. Global rates of growth in both population and GDP have slowed over time with highest average growth rates experienced in the 1970s and lowest growth rates since 2000 (see Figure 1).

Economic growth was also quite variable within individual decades. A period of high growth of the world economy came to an abrupt halt in 1974 in the wake of the first oil price shock, which was triggered by an oil export embargo by the Organization of the Petroleum Exporting Countries (OPEC). This saw global growth drop below 1% in 1975, with negative implications for major industrial economies such as the United States, Western Europe and Japan, which all had economies geared to low energy prices and the energy inefficient patterns of production and consumption they allowed.

The second oil crisis of 1979 was caused by a sharp decrease in oil production following the Iranian revolution. This led to much higher oil prices over a more sustained period, and was a key contributing factor to a major reduction in global growth in the early 1980s. Over the medium to longer term, some positive effects came from this event. The global experience of high oil price volatility led to large investments in improving energy efficiency in many countries, both in industrial processes and in consumption e.g. the average fuel mileage of automobiles increased significantly over this period. This locked in higher energy efficiency for many years into the future, efficiencies which endured long after oil prices crashed in subsequent oil gluts. Also, major investments in diversifying supplies of energy away from dependence on the politically volatile Middle East were made, increasing energy supply security and diversity.

The Latin American debt crisis of the early 1980s led to a lost decade in Latin America, however the worst effects were largely confined to that region. The early 1990s were again a period of slowing global economic growth, associated with the extreme economic dislocation which accompanied the dissolution of the former Soviet Union, and flow-on effects for Council for Mutual Economic Assistance (Comecon) economies more generally. Another significant event was the First Gulf War in 1990–91 and the associated disruption this caused in petroleum markets. The Asian financial crisis of 1997 started in Thailand and saw considerable economic downturn in Southeast Asia and Japan. The Asian crisis coincided with the burst of the dot-com bubble in 2000 with very large impacts on global stock markets. The only period of global recession was the global financial crisis (GFC) of 2008 which many economists consider the worst economic crisis since the great depression of the 1930s. The GFC led to negative global economic growth in 2009 with slow recovery in many parts of the world, especially Europe and the United States.

The GFC was triggered by a housing bubble burst in the US threatening major financial institutions, which were subsequently largely bailed out by the US Government, but which

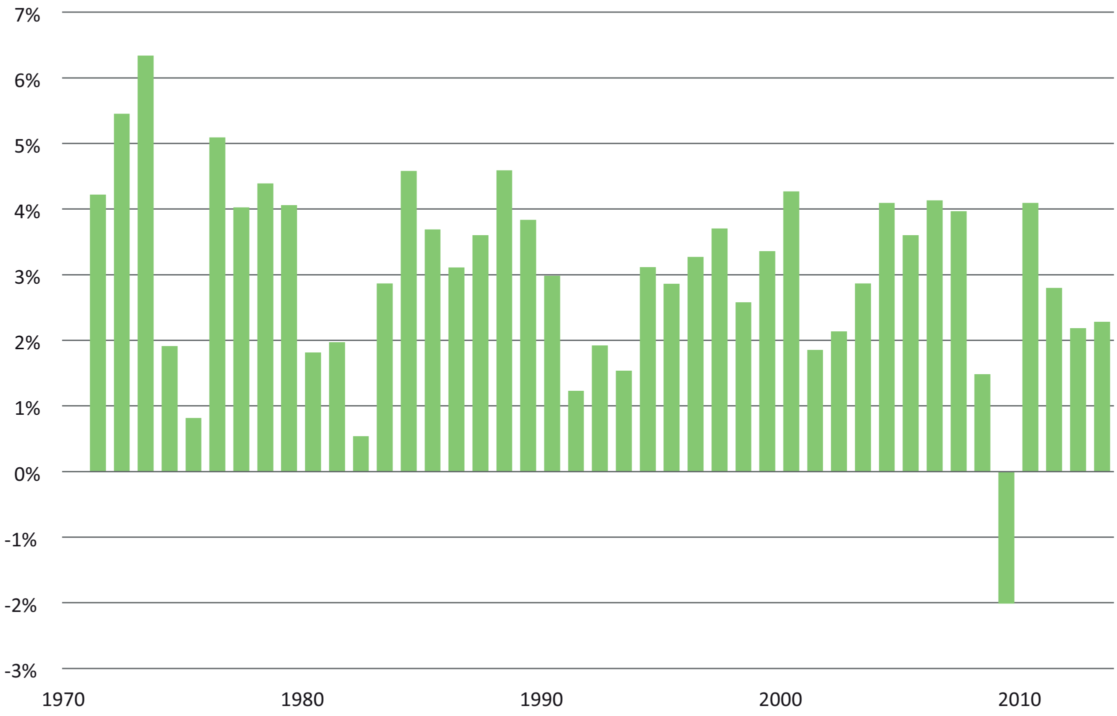

Figure 1. Yearly global economic growth rates, 1970–2013

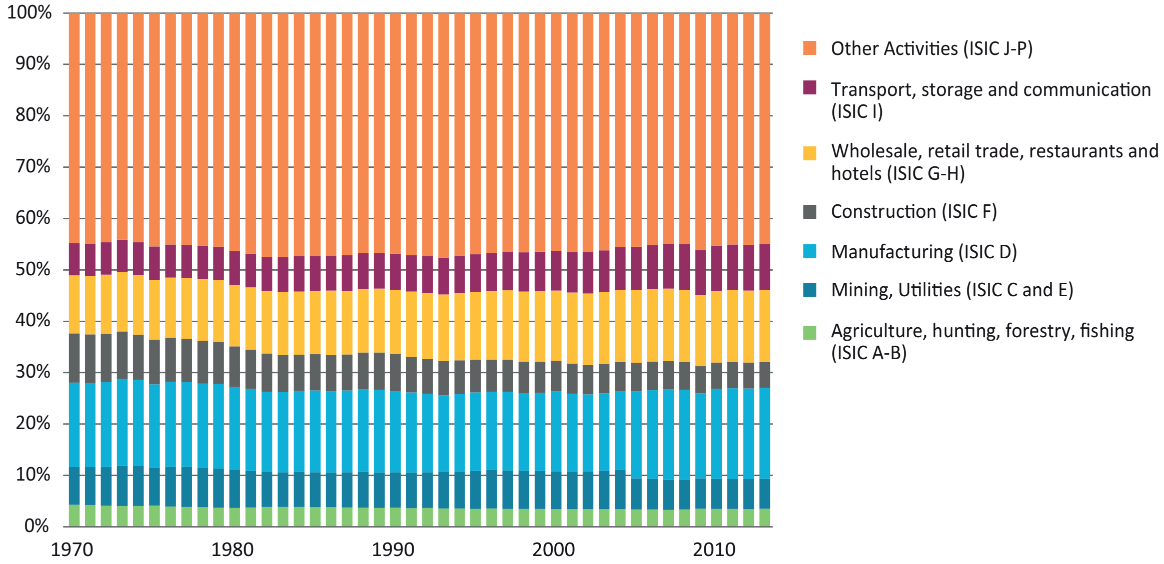

Figure 2. World GDP sector added value shares

nonetheless triggered a global recession from 2008 to 2009. Ongoing ripple effects contributed to European sovereign debt crises, and precipitated widespread austerity measures there. Some other countries which were not already heavily in debt at the onset of the GFC pre-empted any local economic slowdown by instigating economic stimulus programmes (most notably in China). The GFC had comparatively little discernible effect on growth in China and other BRIC economies.

Interestingly, Figure 2 shows that the shares of global GDP attributable to the value added in different sectors have not dramatically changed over the past four decades. A similar situation exists for global expenditure shares, as shown in Figure 3. A little less than half of global GDP is produced by the services sector, with manufacturing, then combined trade (retail and wholesale) and hospitality being the second and third largest contributors to global GDP.

The material intensities of the different sectors shown in Figure 2 are very different, with primary sectors, manufacturing and transport having much higher material intensity than services. Structural change in the world economy would hence affect material intensity, but Figure 2 shows that such change has been quite limited at a global scale.

Indeed, the extent to which the global economy can be shifted further towards the (apparently) more material-efficient sectors is an open question. The analysis in Kander (2005) is particularly interesting with regard to the dynamics behind the growth in the share of the services sector in many advanced economies. A key point from that work is that a major driver behind increasing services

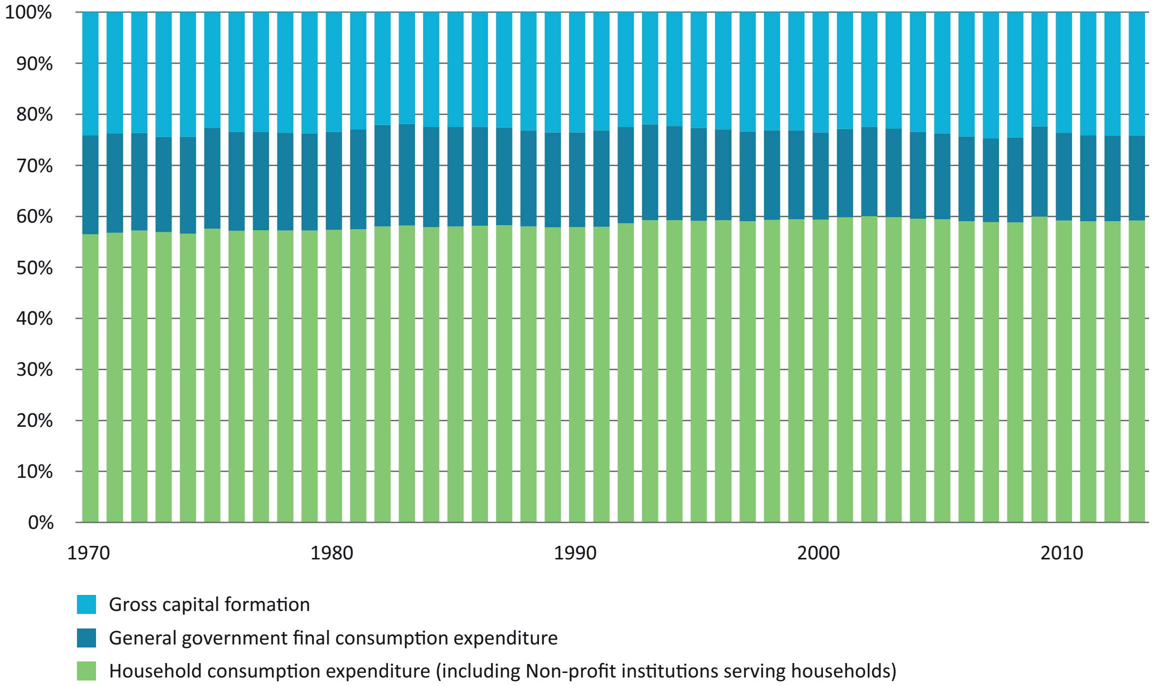

Figure 3. World GDP expenditure shares

shares in some countries is the fundamental inability of many services to greatly increase productivity, in contrast to many primary and manufacturing industries. In effect the service sector becomes relatively more important due to services remaining expensive, while primary commodities and manufactured goods become cheaper per unit, even as they produce ever-increasing quantities (notwithstanding recent commodity price increases). This is important as the (apparent) shift towards services is really founded on ever more efficient and increasing materials extraction, processing and fabrication. From this perspective, services are thus not really substituting for materials- and energy-intensive processes at all.

In Figure 3 we see that household consumption expenditure has been the largest expenditure category, at just under 60% in 2013 with this level remaining reasonably constant over the four decades examined. Capital expenditure was next, followed by government consumption.

When material demand accelerates in periods of rapid economic growth, the supply systems for primary materials such as mines, quarries, farms, forests and fisheries can become stressed by demand outstripping their existing production capacity. The resulting imbalances between global material supply capacity and demand will frequently be expressed in a price increase in world market prices for energy, timber, metals and minerals, and food. These elevated prices will persist until sufficient additional capacity is built, a process which typically requires several

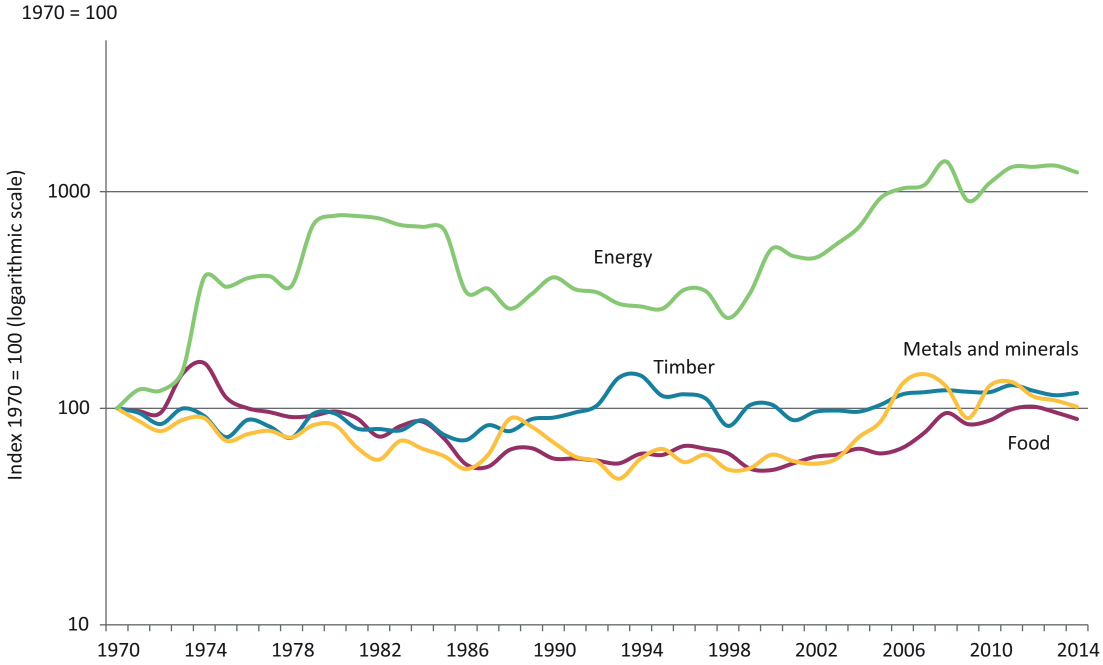

Figure 4. Trends in global resource prices, 1970–2010, indexed

years, perhaps up to a decade. In Figure 4, which shows trends in global resources based on World Bank commodity price data, we see the effects of this quite noticeably in the response of all four basic commodities to the China-led growth of the new millennium (note that Figure 4 uses a logarithmic vertical scale). The rapid run-up in commodity prices had largely ended by 2008, from which point prices stabilized[2].

Also clearly seen in Figure 4 is a decrease in non-energy commodity prices following the 1970s oil shocks, resulting in part from decreased economic growth caused by the rapid increase in energy prices. A subsequent major fall in energy prices from the mid-1980s, sustained for over a decade, is partly from the lagged response of new supply infrastructure being put in place in non-OPEC countries, and partly from lagged efficiency gains among petroleum consumers.

Figure 5 emphasizes the very rapid growth in volumes of four major primary commodities which took place in the first decade of the twenty-first century, the rapid slump brought on by the GFC, and the relative stabilization since. The volatility of energy, and of metals and minerals, is interesting in that they are two categories where the rate of use is limited mainly by the rate at which new infrastructure can be put in place to exploit a very large (but non-renewable) stock. Food is less volatile, perhaps due to it being limited by available arable land. It is nonetheless still quite responsive, as inputs can increase yields per

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[2] At the time of writing, in early 2015, there had been major price decreases for many commodities since mid-2014. This is not reflected in Figure 5.

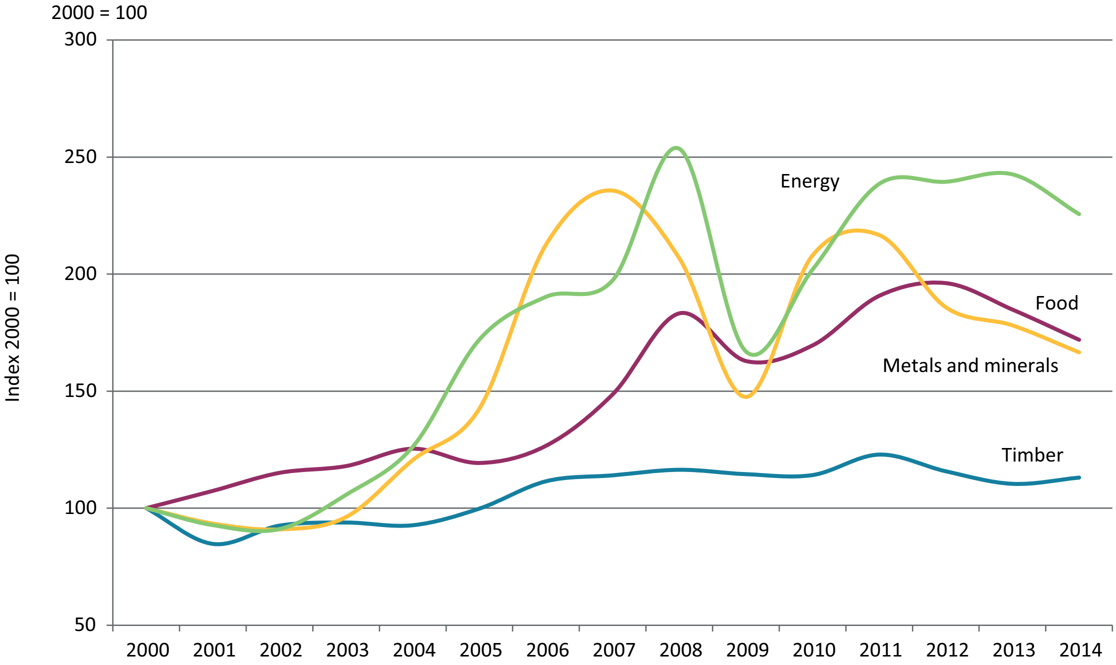
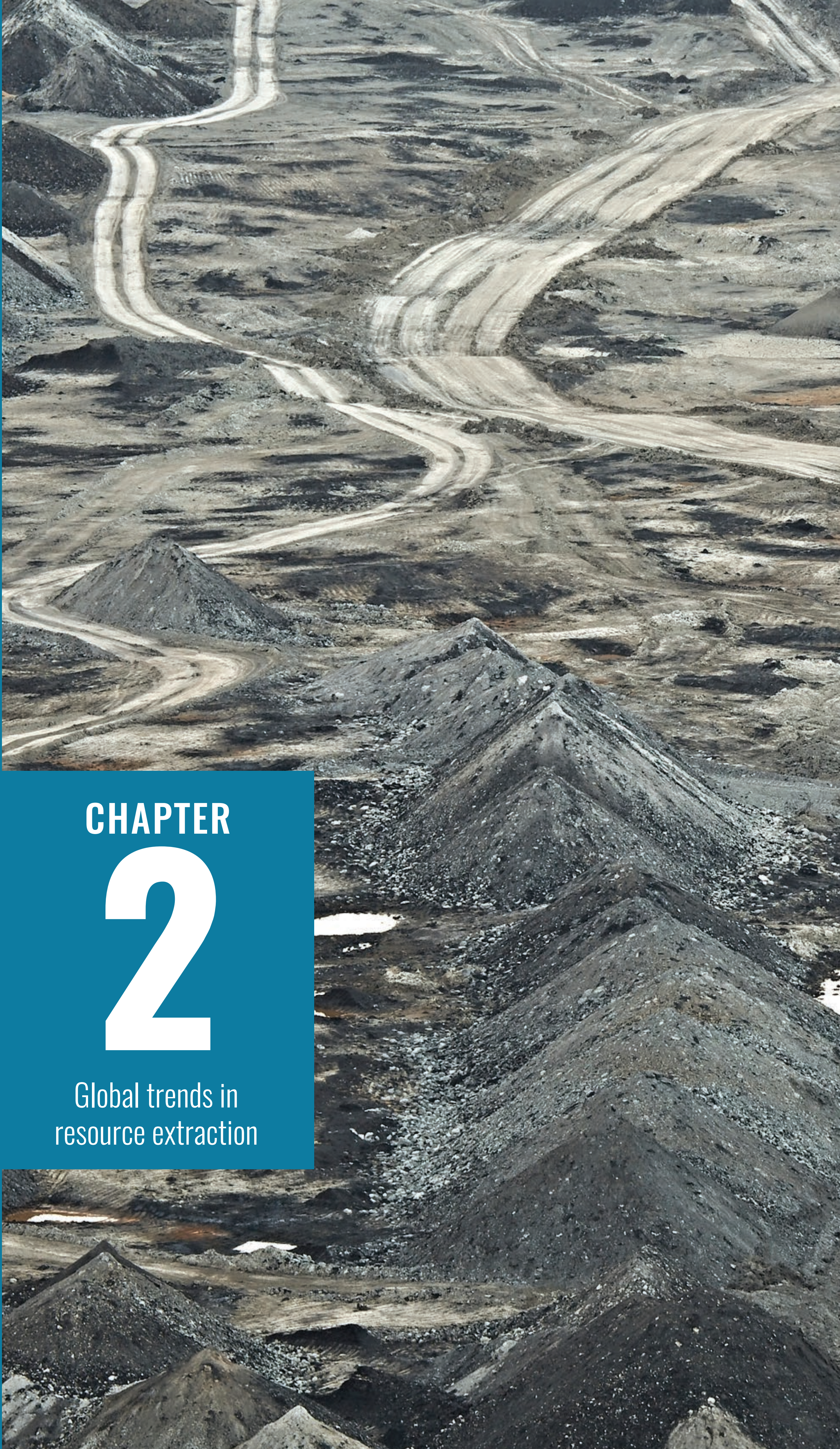


Figure 5. Trends in global resource prices, 2000–2014, indexed

unit of land. By far the least volatile is timber. This might be indicative of a resource that is already being exploited at near maximum sustainable yield. Certainly increasing the actual stock of trees upon which harvest depends can't respond rapidly to increased inputs.

The economic success story of the twentieth century of Europe, the United States and Japan post-WWII was enabled by stable or decreasing world market prices for most natural resources. Since 2000, the price of many natural resources has started to grow, creating a new economic context of higher and perhaps more volatile prices for primary materials. After the GFC the price of many primary materials remained at a significantly higher level, compared to most of the twentieth century.

Most recently, growth in China has slowed and the demand for primary materials has come down significantly, including for coal, crude oil and copper but not to the same extent for iron ore. At the time this assessment study is being written it is hard to judge what the trend in prices for primary materials is going to be in the years to come.



CHAPTER 2

Global trends in resource extraction

Global trends in resource extraction

During the past four decades (1970–2010) significant restructuring of the global economy has taken place, creating new centres of production and consumption and bringing countries to the fore which previously had not played such an important role in the world economy, either in their economic power or in their global material use.

One major factor has been continuing population growth, with global population almost doubling over the four decades from 3.7 billion people in 1970 to 6.9 billion in 2010. That means an average growth in global population of 1.6% annually. Population growth has, however, slowed down in the past decade (2000–2010) with annual average growth reducing to 1.2%.

The pronounced growth in global GDP and per capita GDP is testament to large improvements in material standards of living in many parts of the world. This was especially the case in fast-growing cities in many parts of developing Asia which created new employment opportunities and new middle classes. The global economy has grown from US$15.4 trillion in 1970 to US$51.7 trillion in 2010 (at 2005 constant prices) which equals more than a threefold increase at an average annual rate of 3.1%, or double the rate of population growth. Similar to population, GDP growth has also slowed over the past decade to an average annual growth of 2.6%. In addition, growth was heavily impacted by the global financial crisis of 2008–09. Some major economic centres are still in recovery mode.

It is now commonly understood that improved human well-being and reduced poverty in many developing countries, paired with increased economic growth in industrial countries, has come at the cost of increased use of materials – biomass, fossil fuels, metals and non-metallic minerals – which fuel the global economy. Annual global material use reached 70.1 billion tonnes in 2010, up from 23.7 billion tonnes in 1970. Over the past four decades global material use has thus tripled, growing on average by 2.7% annually. In contrast to population and GDP, there was an acceleration in growth in the decade from 2000 to 2010, reaching 3.7% annually.

With an average growth of 3.5% per year, global trade in materials has grown even faster than global materials extraction, surpassing the rate of GDP growth. In 1970, 2.7 billion tonnes of materials (11% of global materials) were traded between countries. By 2010, the amount of traded materials had risen to 10.9 billion tonnes or 16% of global materials. The growth rate of traded materials has not changed much in the past decade, averaging 3.6% annual growth.

Trade in materials, however, has a far greater impact than directly traded volumes may suggest because of large upstream material requirements along the production chain which create waste and emissions in the country that produces the traded goods. In 2010, the material requirement for trade was 2.5 times direct trade. Around 25.7 billion tonnes of materials used could be attributed to trade among countries. That means that more than one third of all materials extracted in the global economy are destined to produce goods for trade. The raw material equivalents of trade grew by 4.6% annually between 1990 and 2010, but growth somewhat slowed over the decade between 2000 and 2010, where it was at 2.8%.

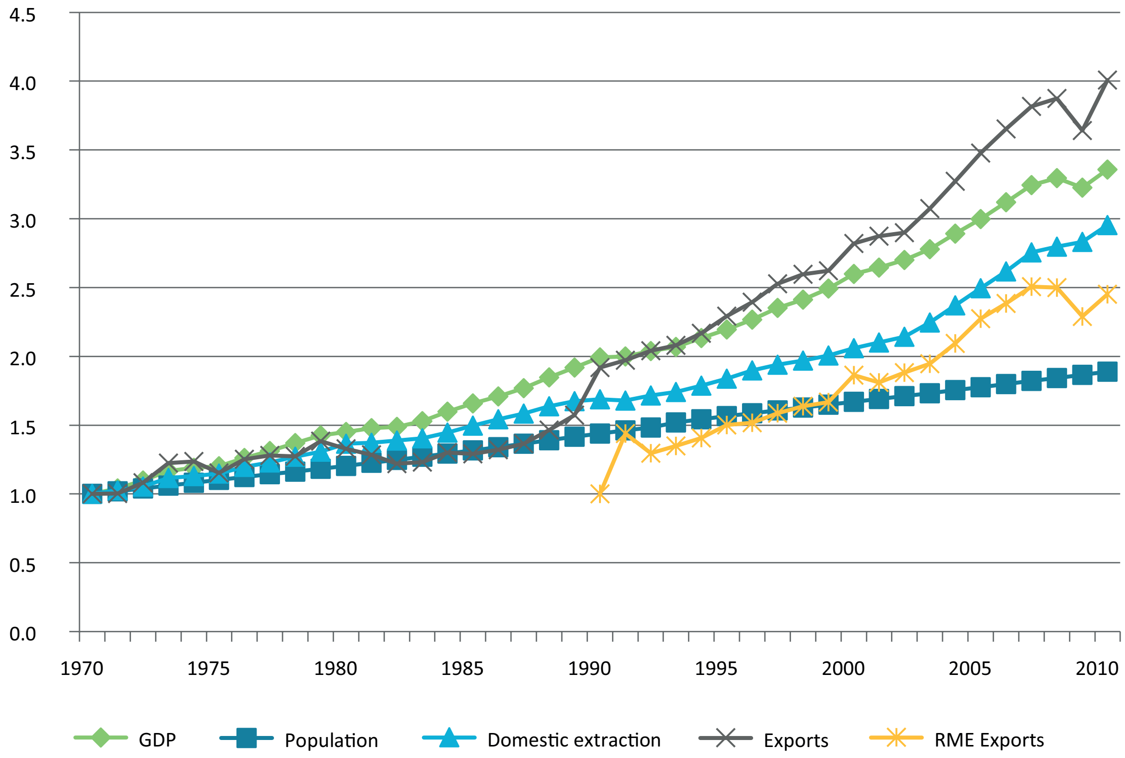


Figure 6. Trends in GDP, population, domestic extraction (DE), exports and raw material equivalents (RME) of exports, 1970–2010, index 1970 = 1

During the past four decades, economic growth has not been without interruptions, nor has it been homogeneous across world regions. There were considerable signs of recession during the oil price shocks in 1973 and 1978 in the industrialized world, where growth depended on cheap energy, requiring adjustments in energy supply and efficiency of energy use. The 1980s were characterized by the debt crisis that unfolded in many parts of Latin America and sub-Saharan Africa, and the late 1990s by the Asian financial crisis. Despite these events, on average the global economy continued to grow substantially and so did material use. Notwithstanding economic fluctuations, the systems of production and consumption and the infrastructure established have required a rising annual throughput of materials to operate, maintain and extend the systems.

The year 2000 seems to mark a turning point, however, changing the long-term relationships between population, economy and consumption. Since that year, global population growth and economic growth have slowed down and fallen below the long-term trend, yet extraction and trade of materials have accelerated. This has led to tremendous increases in global resource prices to the extent that the long-term trend of decreasing costs of materials that marked most of the twentieth century was reversed in the first decade of the twenty-first century (UNEP 2011a). This change in trend and acceleration of global resource use is closely connected to the industrial and urban transformation that has occurred in several emerging economies, most notably in China. The Chinese economy has been characterized by a particularly high level of public and private investment into urban and production infrastructure, which has occurred at the cost of household consumption which was curbed through government intervention and currency policy.

Some have argued that the requirements of China for coal, gas, iron and steel, construction materials and agricultural produce are now slowing dramatically and may have reached their peak. Another country undergoing a transition of the speed and scale of China is perhaps not foreseeable in the near future but nevertheless global material use is on a continuing growth path.

Scenarios for annual global material extraction for 2050 include between 50 and 150 billion tonnes (UNEP 2011a) and 35 to 105 billion tonnes (Dittrich et al. 2012a) based on different assumptions regarding global population and material intensities, and scenarios for a shrinking global economy, and 90 to 180 billion tonnes (Schandl et al. in print) based on coupled economic and physical stocks and flows modelling.

A recent study (Bringezu 2015) identified a potential sustainability corridor based on an indicator for Total Material Consumption of abiotic resources ranging from 6 to 12 t/person, the Total Material Consumption of biotic resources not exceeding 2 tonnes per person, and the Raw Material Consumption of used biotic and abiotic materials ranging from 3 to 6 tonnes per person by 2050. For policy, a "10-2-5 target triplet" can provide orientation, when the three indicators are assigned values of 10, 2 and 5 tonnes per person, respectively.

Figure 7 shows the increase in global material use by four main material categories. All four material groups have grown over the past four decades. Biomass extraction grew by 2%, fossil fuels by 1.9%, metal ores by 2.8% and non-metallic minerals by 4% per year on average. The different growth rates for different materials have changed the contribution of these materials to overall global material use. The share of biomass decreased from 37% in 1970 to 27% in 2010, and the share of fossil fuels from 26% to 19%. Metal ores stayed

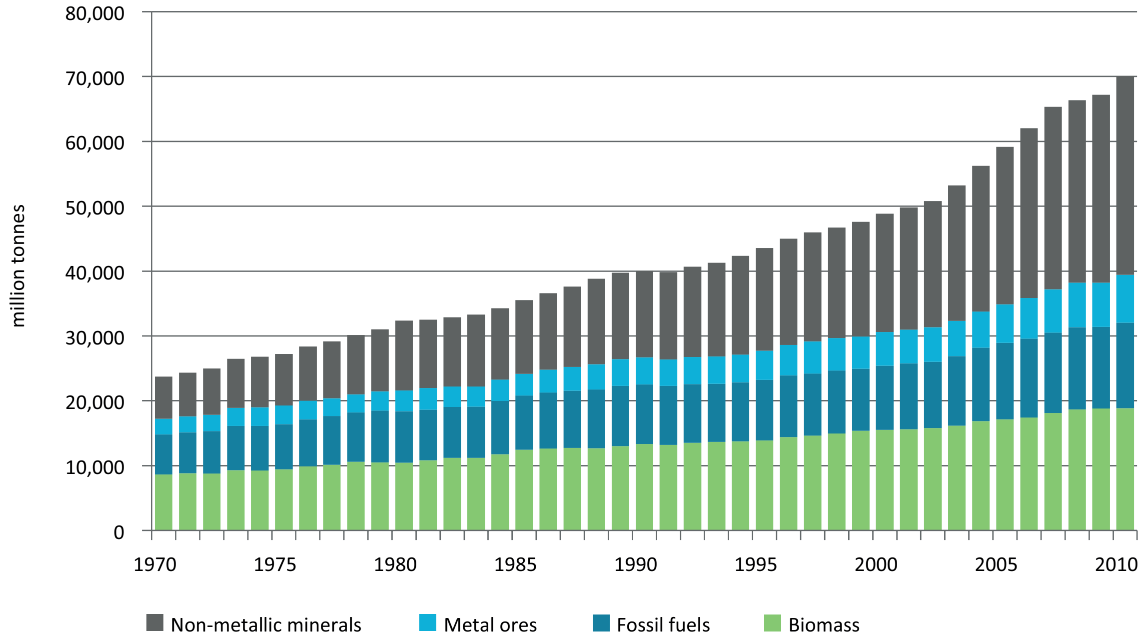


Figure 7. Global material extraction (DE) by four material categories, 1970–2010, million tonnes

constant at a share of around 10%, and non-metallic minerals increased from 27% to 44%.

During the 2000 to 2010 period all materials except for biomass accelerated growth in extraction (fossil fuels grew by 2.9%, metal ores by 3.5%, and non-metallic minerals by 5.3% on average since 2000); growth in biomass extraction remained constant at 2%.

Since global material use has grown faster than population, we see in Figure 8 that per capita use has increased quite significantly, especially since 2000. It took 30 years for per capita material use to grow from 6.4 tonnes in 1970 to 7.9 tonnes in 2000 but only another 10 years to reach 10.1 tonnes per capita in 2010. By that time, the average use of materials per person included 2.7 tonnes of biomass (mostly related to food supply systems and including timber as a structural material and for heating), 1.9 tonnes of fossil fuels (mostly for power and transport), 1.1 tonnes of metal ores (for construction, manufacturing applications and communications) and 4.4 tonnes of non-metallic minerals (for buildings and transport infrastructure in fast-growing cities).

The potential for circularity of the global economy and the potential for recycling have been assessed as somewhat limited (Haas et al. 2015) because of large amounts of biomass and energy carriers that have little potential for recycling and construction minerals ending up in long-lived stocks. The study indicates that strategies targeting the output side of material flows (end of pipe) are limited given present proportions of flows, whereas a shift to renewable energy, a significant reduction of societal stock growth, and decisive eco-design would be required to advance the global economy towards a higher level of circularity.

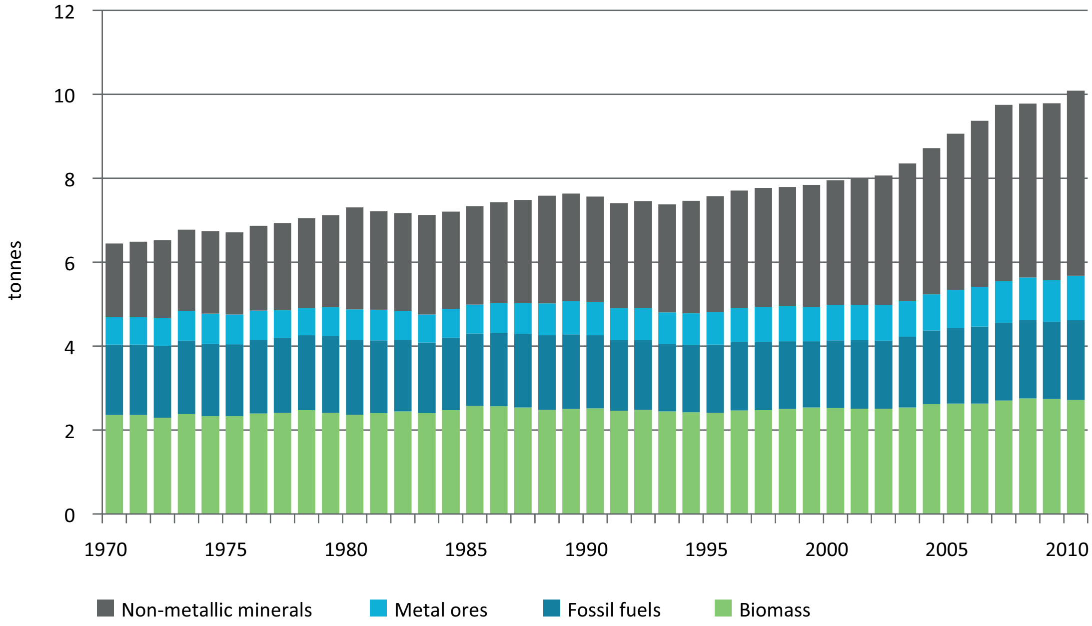


Figure 8. Per capita global material extraction (DE) by four material categories, 1970–2010, tonnes

Extraction of non-renewable materials, most notably of fossil fuels and metal ores, inevitably reduces the global stocks of these materials available for use in the future. At some point, ongoing and increasing exploitation must lead to serious depletion of global deposits of these materials. Unfortunately, actually estimating when such depletion may become an important problem for any individual class of mineral would be an extremely complex task. The main stumbling block is defining what the remaining global in situ recoverable stock of any mineral is. A common error made by some is assuming that there is some close relationship between the current reserves of a mineral, for which global estimates are available from the USGS, for example, and the ultimate quantity of that mineral remaining which might be recovered. If this were so, it would be a simple matter of dividing the reserve by the average expected rate of extraction, to arrive at the years remaining until all viable stocks of the mineral had been mined. In Table 2 this calculation has been performed for a number of key commodities, using reserve estimates from the sources listed, and assuming current extraction rates continue.

Table 2. Recoverable reserves of key commodities

	Recoverable reserve	Global extraction in 2010	Years of available reserve at 2010 extraction level
Oil	233 billion tonnes[1]	3,573 million tonnes	65
Coal (bituminous and lignite)	1,318 billion tonnes[1]	7,025 million tonnes	188
Natural gas	176 billion tonnes[1]	2,609 million tonnes	67
Iron ore	190 billion tonnes[2]	2,634 million tonnes	72
Copper ore	100 billion tonnes[2]	1,877 million tonnes	53
Bauxite and Alumina	28 billion tonnes[2]	226 million tonnes	124

Sources:

[1] World Energy Council (2015) https://www.worldenergy.org/data/resources/

[2] USGS Mineral commodity summaries 2015a

The problem with this approach is that it will systematically underestimate the ultimate quantity of recoverable commodities, by an unknown but generally vast amount (multiples to orders of magnitude). The basic problem is that "reserves" generally only include those portions of mineral deposits which have been found, closely defined (usually by costly drilling and chemical analyses), and can be economically exploited using current technologies and at current prevailing prices for the commodity involved. It is thus a highly dynamic quantity, which will vary widely according to changing market prices and advances in technology, *even before the effect of conducting further exploration is considered*. Reserves should thus be thought of as an extraordinarily conservative lower limit on a commodity's ultimate availability at current prices, with little real linkage to ultimate availability should that commodity's market value rise. Even with a commodity such as copper, which has been highly valued (and thus searched for) for centuries, the global reserves in 2014 of 700 million tonnes were over twice 1970 reserves of 280 million tonnes, despite an additional 480 million tonnes having been extracted in the intervening 44 years (USGS 2015c). A similar phenomenon is clear for reserves of petroleum, where Miller and Sorrell (2014) show the global reserves to production ratio climbing from approximately 30:1 in 1980 to well over 50:1 by 2010 (at which time the fracking revolution in the US was only just beginning to significantly expand supply).

"Resources" is a second, generally much larger quantity that is also sometimes used as a more inclusive guide to recoverable stocks. Different categories of resources exist, each defined in different ways, however one thing they usually have in common is that (unless specifically stated otherwise), they again refer only to current, discovered deposits. Key differences with reserves are that some classes of resources may not be well defined by actual physical sampling, but rather just inferred from geological continuity of existing deposits. Also, economic extraction of a resource need only be potentially feasible, *not necessarily at current prices or using current technology*. Using copper as an example again, using the discovered resources figures given in USGS (2015b) would expand the apparent stock of copper threefold over reserves.

A third, much more speculative category is also put forward in USGS (2015b), an estimate for a further 3.5 billion tonnes of copper in "undiscovered resources". The method employed in estimating this "known unknown" is set out in Johnson et al (2014). If one accepts that including this last category does set a realistic upper limit on recoverable copper, this adds a further five times 2014 reserves to in situ copper stocks. The above discussion should help illustrate just how uncertain any attempt to define ultimate stocks is, even for the best understood and most intensively explored-for minerals. Most minerals have not been explored for anywhere near the degree that copper or oil have been. The key point here is that while supply interruptions can happen for a variety of reasons (wars and political intervention, underinvestment in developing inventories due to depressed prices, etc.), it is hard to envisage any ongoing supply problem arising from global depletion of any major commodity for many decades yet.

The natural resources are far larger than the economically viable and technically accessible reserves and some of those resources may well become accessible as extraction technologies improve and prices change. Additional investment in exploration in the past has usually led to an increase in natural resource stocks and reserves and it is not easy to establish an absolute resource limit for most natural resources. It appears, however, that resource depletion is not going to be a pressing issue before the middle of the century. Increasing environmental impacts from resource extraction, social conflicts and rising costs may lead, however, to supply shortages of primary materials that are strategic for industrial production.

The resource stocks and reserves are not evenly distributed around the globe which necessitates trade flows and primary material imports for such regions that lack materials that are critical for production systems. The amount of materials traded among countries globally has grown faster than material extraction. Growth rates are expected to be higher for materials that are not commonly available in every country, such as metal ores and fossil fuels, and lower for materials such as construction materials that are usually available locally.

Trade in metal ores grew by 4.7% annually on average over the past four decades but accelerated to 7% annual growth between 2000 and 2010. In 1970, 370 million tonnes of mostly concentrated metals were traded. In 2010, metals traded totalled 2.4 billion tonnes, comprising 22% of all traded materials.

Trade in biomass has also grown dramatically from 370 million tonnes in 2010 to 1.9 billion tonnes in 2010. Biomass trade grew at an average of 4.2% over the past four decades and has somewhat declined since 2000 to 3.2% yearly average growth.

Trade in fossil fuels, which comprises the largest share in materials traded at slightly more than 50% of all traded materials, remained at a constant 2.8% yearly increase over the past 40 years and did not change between 2000 and 2010. In 1970, 1.8 million tonnes of oil, coal and gas were traded among countries, accounting for two thirds of all traded materials. The amount of traded fossil fuels had grown to 5.6 billion tonnes by 2010.

Non-metallic minerals is the material group that is least likely to be traded, and amounts were below 10% in 2010 at one billion tonnes. This group of materials experienced the highest annual average growth of 5%, starting from a very low level of 145 million tonnes in 1970 – a time when construction materials were hardly traded at all.

Per capita trade of materials doubled over the four decades from 1970 to 2010, from about 0.8 tonnes per capita to 1.6 tonnes per capita.

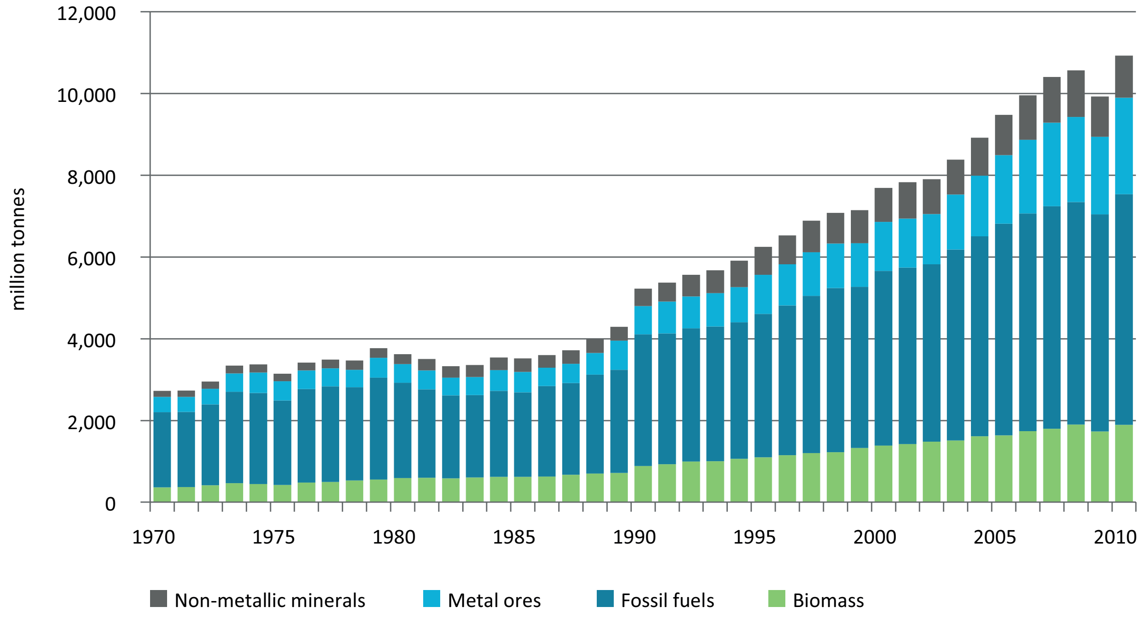


Figure 9. Global exports of materials by four material categories, 1970–2010, million tonnes

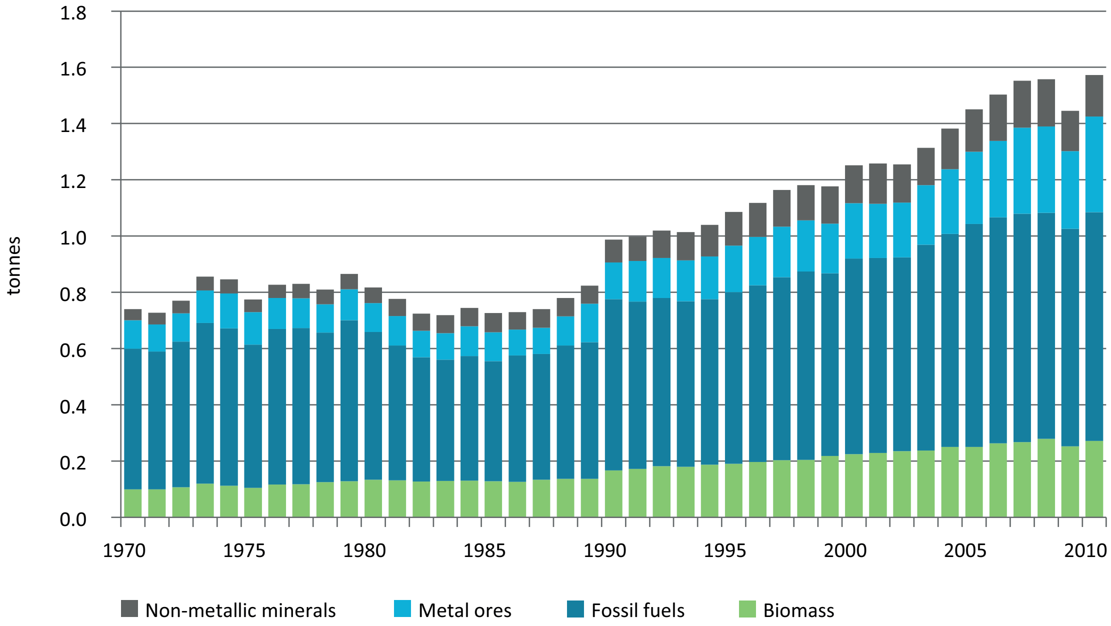


Figure 10. Per capita global exports of materials by four material categories, 1970–2010, tonnes

When considering the whole supply chain, material requirements for trade must be accounted for by adding materials that have been mobilized for producing traded products in the country of origin. In comparison to direct trade we see that by taking a broader perspective trade has far greater implications. It also becomes apparent that the contribution of the different materials needed to produce traded goods is quite different from direct trade flows.

The relative importance of fossil fuels to produce traded goods is much smaller than the direct import of fossil fuels suggests. It accounts for one quarter of all upstream material requirements. By contrast, non-metallic minerals now appear of much greater importance when we attribute the amount of non-metallic materials required to build factories and roads that have been utilized for the production of export goods.

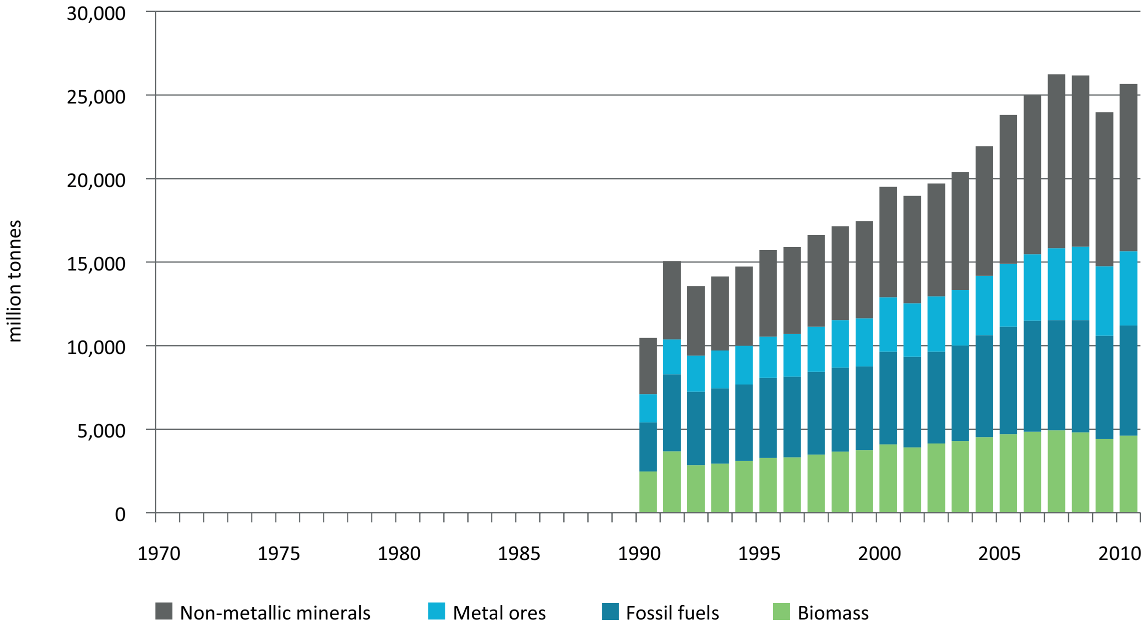


Figure 11. Global raw material exports by four material categories, 1990–2010, million tonnes

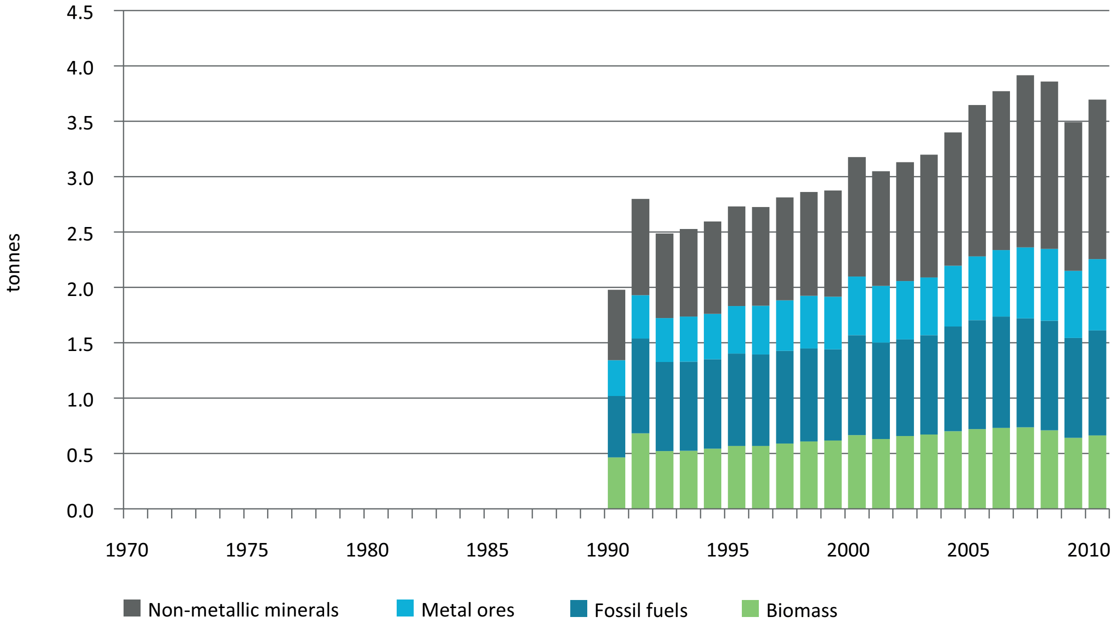


Figure 12. Per capita global raw material exports by four material categories, 1990–2010, tonnes

The rapid increase in per capita global material use (the metabolic rate of the global economy) from 7.9 tonnes to 10.1 tonnes per capita in just 10 years since 2000 and the fact that materials use grew faster than GDP over that decade has meant that global material efficiency, for the first time in a century (Krausmann et al. 2009), has started to decline. Since 2000, we have observed growing material intensity (MI) in the global economy. In 2000, 1.2 kg of materials were required to produce one US$ of GDP; this had risen to almost 1.4 kg per US$ by 2010. The main reason for the increase in material intensity at the global level is a shift of global production away from very material-efficient economies – Europe, the United States, Japan and South Korea – to the less efficient economies of China, India, Brazil and South Africa among others.

Material use is a good proxy for overall environmental pressure (Haberl et al. 2004) and also reflects environmental impacts, so decreasing material efficiency is not favourable with regard to environmental sustainability. It means that the speed at which we are exploiting natural resources, and generating emissions and waste, is increasing faster than the economic benefits gained. This disproportionately accelerates environmental impacts such as climate change, resource depletion and reduced ecosystem health.

The figures also show that global decoupling has not occurred over the past decade. Earlier improvements in material efficiency have reversed during the great acceleration of socio-metabolism that has occurred since the year 2000. The dynamics behind this increase in material intensity are complex. One factor is the rapid increase in total material flows which typically occurs when traditional agrarian systems of production and consumption are replaced by modern industrial ones. This is because traditional systems are largely biomass based and so limited by their reliance on sustainable flows of biomass, whereas modern systems are largely minerals based and so limited (in the short term) mainly by the rapidity with which these mineral stocks can be exploited. This is central to the whole socio-metabolic transition phenomenon (Haberl et al. 2011). The above demonstrates that the metrics used in the quest for sustainable materials management at the global level must be seen against the backdrop of the very rapid industrial transformation currently taking place in many parts of the developing world.

This large increase in material flows is not, however, sufficient to precipitate increasing MI. Indeed the reverse is often the case, with MI typically decreasing as monetary gains increase faster than material throughputs. This phenomenon has been observed for many countries and is well illustrated, for example, in the individual country studies contained in UNEP (2013). Explaining the recent increase in global MI requires an additional phenomenon, where an increasing share of global economic activity is being performed by nations which have higher MI. The clearest and most important example of this is the large relative shift of manufacturing activity in the Asia-Pacific region from low MI Japan to much higher MI China. Even though both nations have consistently made major improvements in their material efficiency, the rapid change in relative shares has still led to an increase in MI for the region in aggregate (Schandl and West 2010).

It is important to note that the lower MI / higher resource efficiency of richer countries itself is an expected and largely inevitable outcome of aspects of their economic structure. In some cases, more affluent nations have large elaborately transformed manufactures (ETM) sectors, which typically add great value to each unit of material throughput. This is a clear case of using materials more efficiently. However, some affluent countries have industrial sectors dominated by low value added primary and processed primary production. There are also a number of poor countries which have much higher proportions of their industrial sector in ETMs than some affluent countries, which nevertheless still exhibit high MI.

A second dynamic which can help explain this latter situation is that affluent countries tend to have relatively large service sectors, which also add more value per unit of material consumed than primary industries. There is however one important but easily overlooked additional factor, which of itself greatly reduces most affluent countries' MI. The simple property of being affluent generally implies a high wage cost structure, which in turn means that the value added for an identical labour intensive service will be much higher in a rich country than a poor country. This directly improves the apparent material efficiency of wealthy countries relative

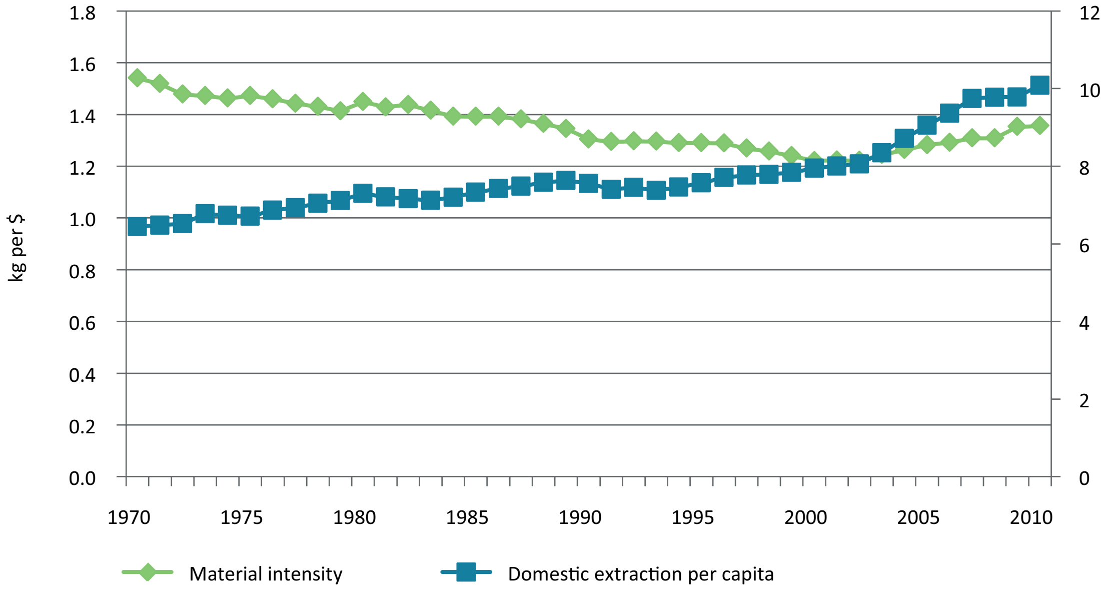


Figure 13. Global material intensity (DE per unit of GDP) and metabolic profile (DE per capita), 1970–2010, kg per $ and tonnes

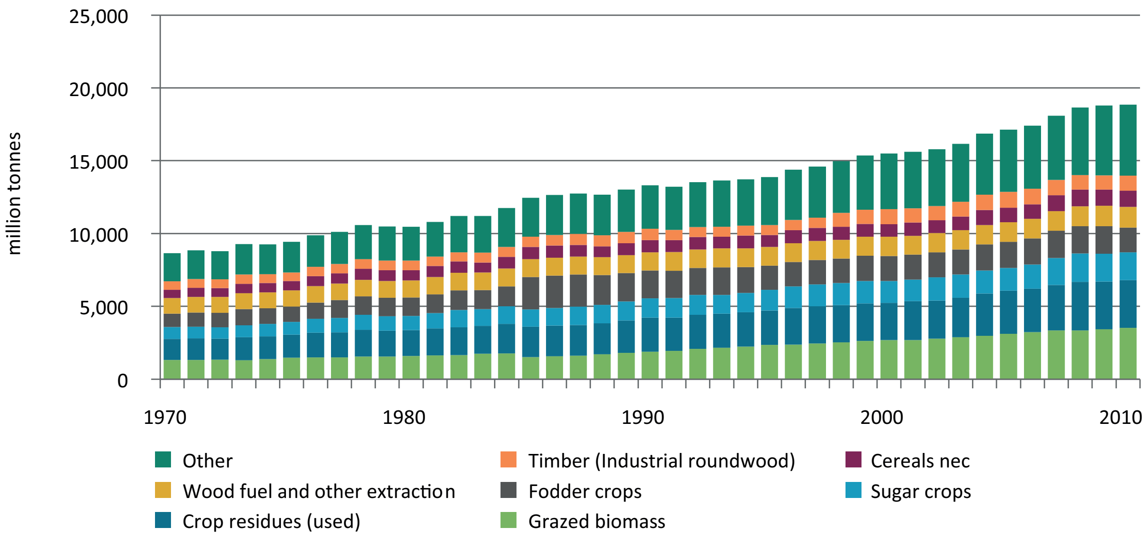


Figure 14. Global extraction (DE) of biomass by material subcategories, 1970–2010, million tonnes

to poorer countries, especially when the GDP measure used is exchange-rate based.

The detailed disaggregation of DE of biomass in Figure 14 shows that the relatively slow growth trend for this category was most pronounced for the two wood categories, Timber (industrial round wood) increasing by a total of 76% and Wood fuel by only 32% over the full four decades. The higher growth for Timber (industrial round wood) probably reflects there being a number of alternative uses for it in an industrial society, even as it become less important as a structural material. Paper is perhaps the most obvious example. Wood fuel, on the other hand, will tend to be largely replaced by other energy sources as a society modernizes, and where former fuelwood finds alternative uses, it will usually be reclassified under Timber (industrial round wood). The grazed biomass category grew the fastest, increasing by 164% however given the uncertain separation between this category and fodder crops, they should probably be taken together, in which case total growth over the full period for the two combined was 131%, still relatively strong growth within the biomass category, and consistent with an increase in the consumption of animal products as societies become more affluent. Sugar crops showed the strongest total growth for any of the major "pure" categories (137%), and this is consistent with the increasing importance of processed foods as developing countries urbanize. The aggregated "Other" category grew by 150%, where growth was dominated by increases in Vegetables and Oil Crops.

The relatively subdued growth of biomass as a category probably also reflects some natural constraints on the ability to arbitrarily increase harvests. This is clearly relevant for forest products, where deforestation has become a major environmental issue in many countries (Foley et al. 2005), however there are also major limitations on the availability of arable land for crops (Lambin and Meyfroidt 2011). Increasing inputs such as fertilizers and pesticides can increase productivity on available land, but often with rapidly diminishing returns and the associated costs of land degradation. If this approach is pushed too far, a situation can develop where arable land becomes a depleting stock which is effectively being "mined". Furthermore, total land area remains constant, so expanding

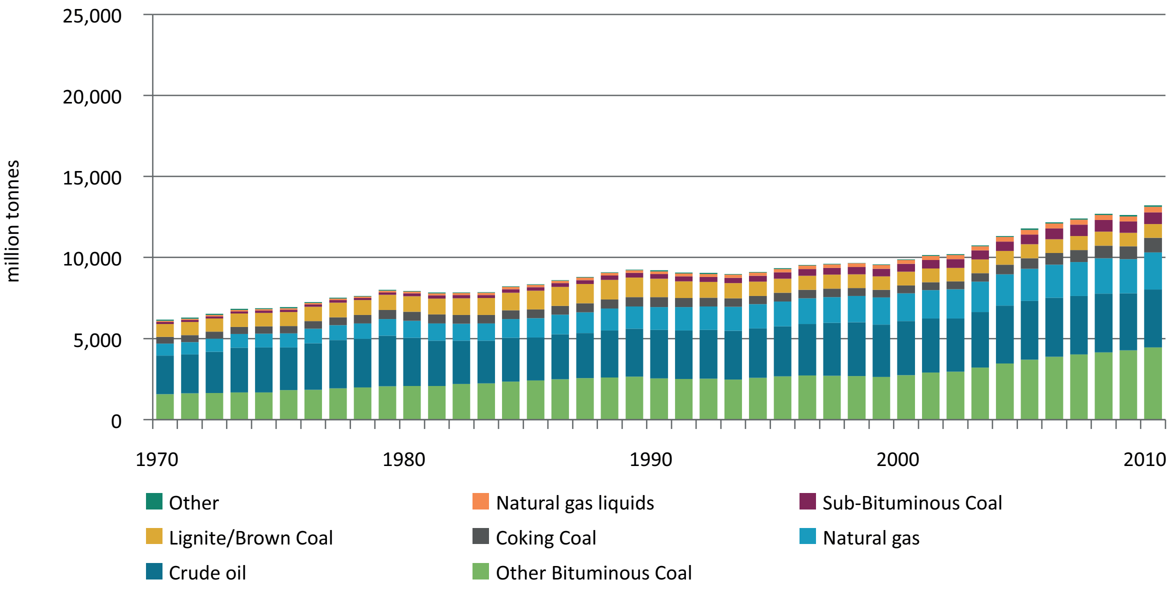


Figure 15. Global extraction (DE) of fossil fuels by material subcategories, 1970–2010, million tonnes

agriculture into existing forest areas will decrease land available for forestry, and vice versa. It is possible (indeed commonplace) to bring land from previously low productivity areas, e.g. deserts, into biomass production by transferring water from remote river systems, or pumping from aquifers, however this is usually limited by the expense of developing the infrastructure required, the adverse effects it has on source river systems, and/or by the rate at which the rivers or aquifers can provide. Many aquifers are in effect non-renewable resources on human timescales, with recharge periods of thousands of years or more.

The data on DE of fossil fuels in Figure 15 are disaggregated into eight categories, showing that total DE for each of the categories grew by over 100% between 1970 and 2010. By far the largest growth in total tonnage terms was for other bituminous coal, which increased by nearly 2.9 billion tonnes, almost twice the 1.5 billion tonne increase for natural gas, which had the second largest increase in total tonnage terms. These two categories grew at roughly comparable rates (2.6% p.a. and 2.8% p.a. compounding, respectively), with the rate of growth in other bituminous coal accelerating over the 1990 to 2010 period, while the fastest growth for natural gas was from 1970 to 1990. All coal categories together accounted for over 58% of the 7 billion tonne increase in fossil fuel tonnage between 1970 and 2010, increasing coal's share of total fossil fuels from 48% to 53%, while natural gas increased from 12% to 17%. The expanded share of coal and natural gas came largely from crude oil, which decreased from 39% to 30% over the full period.

There are a number of possible reasons for this change in fossil fuel mix over time. Perhaps the first to come to mind is the relative cost per unit of energy delivered, of coal and gas over oil, however this relationship is not always straightforward, especially when comparing natural gas and oil[3]. Another factor is security of supply. Concern has been expressed over the possible depletion of oil reserves on a two to three decade scale since the early twentieth century, however this has not affected its growing dominance. In the 1970s, this ongoing concern over supply was hugely augmented by a very real demonstration of the ability of OPEC to restrict supply, and of the vulnerability of the world oil supply (and so prices) to political instability in the Middle East. The impact of the first oil shock is clearly visible in the decrease in total oil extracted in 1974, with a much larger and more protracted decline following the second oil shock in 1979. The two oil shocks and the economic dislocation they wrought made decreasing reliance on oil a real priority of major economies at that time. Towards the end of the twentieth century, fears of an approaching peak in oil production, and decreasing energy return on energy invested (EROEI) for oil in particular became prominent, both of which would imply higher oil prices in the future.

Fears over security of supply due to political factors were further reinforced by the two Gulf Wars. A final factor which probably influenced changing shares between the three main fossil fuel groups was concern over increasing emissions of GHGs, and the measures taken to reduce them. This last factor would favour an increased role for natural gas, which has relatively low GHG emissions for a fossil fuel. Conversely, it should act against the expansion of coal. As can be seen in Figure 15, this is not what happened with regard to the main categories of coal, which increased rapidly in the new millennium. A major decrease in the share of lignite, the worst GHG emitting class of coal, did occur, but the majority of this happened in the immediate aftermath of the dissolution of

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[3] Analysing data published in BP (2013), it appears that coal has a consistent major cost advantage over oil. Comparing the years 1990–2012 for OECD oil with Japanese steaming coal, on a cost + insurance + freight basis, oil is around 2.8 times more expensive per unit of energy delivered. In contrast to this, when comparing natural gas to oil, we find that in some cases there are only marginal differences. For LNG delivered to Japan between 1984 and 2012 the cost advantage of LNG was negligible (less than 2%). On the other hand, compared to non-liquefied natural gas in Alberta from 1990 to 2012, oil was on average 2.6 times more expensive.

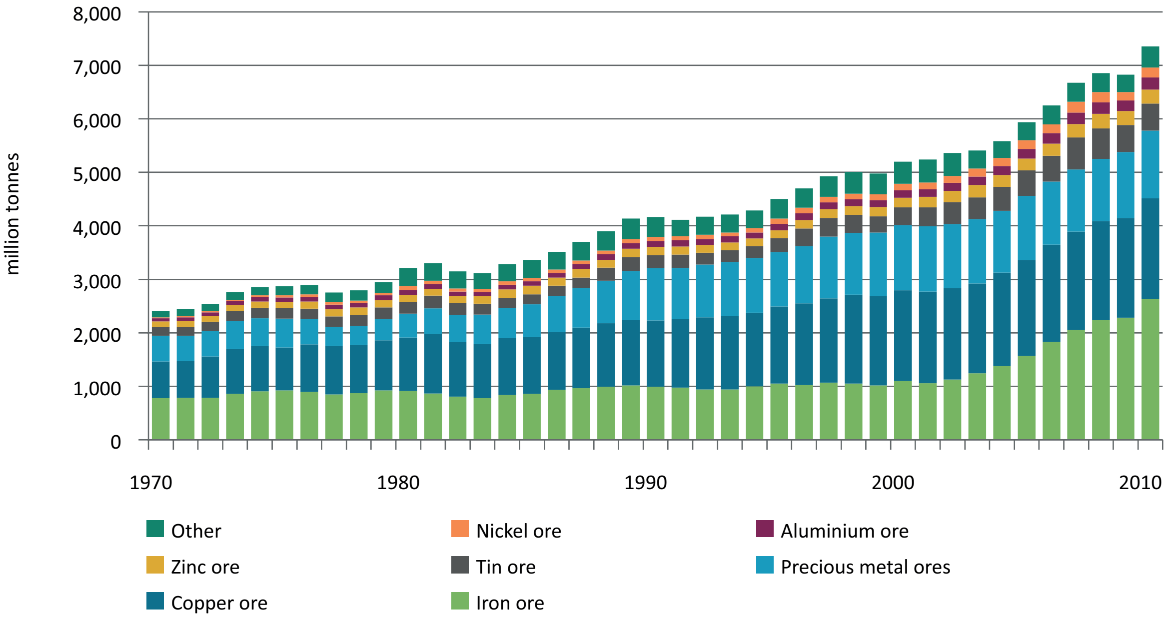

Figure 16. Global extraction (DE) of metal ores by material subcategories, 1970–2010, million tonnes

the Eastern Bloc, and can mainly be attributed to the closure of non-competitive industries in Central and Eastern Europe. The acceleration of the rise in coal in the new millennium is largely attributable to rapid industrialization in China, and supplied largely through greatly increased extraction from its huge domestic deposits of coal, but also from increased imports from ready suppliers in its region.

The data on DE of metal ores in Figure 16 are disaggregated into eight categories, and show that total DE for each of the categories grew by over 250% between 1970 and 2010. Interestingly, while iron ore began and ended the period as the largest single category, for most of the period it was eclipsed by copper ore, such that by 2001 its total tonnage was only 62% that of copper ore. The extremely rapid growth in iron ore DE after that time is explained by China entering a very rapid, and disproportionately steel intensive, phase of growth. The growth rate for iron ore, which had been less than 1.2% p.a. compounding between 1970 and 2000, grew at over 9.1% p.a. between 2000 and 2010. The massive increase in demand for steel from China was dominated by construction. In contrast, the corresponding rates for copper over the same periods were 4.6% p.a. and 0.5% p.a. The reason why the response of copper was so muted is not clear[4]. Nickel experienced by far the most rapid growth rate of any metal ore category, increasing at 6% p.a. compounding from 1970 to 2010, although it showed a similar pattern to copper in that most of its growth was concentrated in the period before 2000. Indeed, all metal ores except iron showed this pattern to some extent,

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[4] The application of ore grades that are fixed over time may have led to a systematic underestimate of some metal ore extraction rates in this report. Conversely, the shift of China towards greater imports of higher grade ore over low grade domestic production might have ameliorated the apparent increase in iron ore consumption. The many issues associated with estimating tonnages of ore extracted, which are typically back calculated from (pure) metal production data, have been extensively discussed within the IRP. A point of general consensus seems to be that there is no real means of achieving anything better than rough guidance for many metals, in the absence of comprehensive and detailed time series data on production and grades at the individual national level. The two key problems are the extreme variability of grades between mines, and the problem of co-production of metals from poly-metallic ores.

with zinc being the least affected, probably through its close association with the use of steel (providing galvanic coatings for steel).

From the vantage point of 2015, one observation that might be made is that the massive price increases experienced by most metals, for much of the decade post-2000, do not appear to have been caused by testing the limits of the Earth's stocks of these materials. They were instead probably a transient result of the time lag between price signals being delivered by markets, and the speed with which the massive infrastructure typical of modern resources projects could be put in place. Iron ore prices averaged over $US167 in 2011, when underlying World mine production was less than 2,940 million tonnes, but averaged under $US97 per tonne in 2014, as increased mine production (3,220 million tonnes) came online. Results for three other metals are provided in Table 3.

The above provides only a very crude indication. To truly have an idea if and when major supply constraints might arise due to serious depletion of the World's non-renewable stocks of minerals, it would first be necessary to have a good estimate of what those ultimate stocks are. Unfortunately, this is not currently the case. While variously defined reserves and resources are commonly calculated, these terms relate more to cumulative exploration that has been undertaken to date for a particular commodity, combined with the current economics of exploiting these known deposits. They do not provide meaningful guidance on how much of a particular commodity will ultimately prove recoverable given further exploration and changing extraction technology. A very brief treatment of the effects of technological change on the availability of some metals is given in West (2011).

While there is little indication that ultimately recoverable stocks of any important metal are near depletion, an important alternative perspective on whether or not the supply of metal ores is assured for the foreseeable future is put forward in Mudd and Ward (2008). In that work, it is noted that rather than depletion of deposits limiting supply, it could be the demands placed on the environment's ability to "sink" emissions (notably GHGs and mine wastes) and to provide inputs such as energy and water which might ultimately restrict supply.

Table 3. Decline of metal prices since 2011 despite increased production. Production data from USGS (2015a), Price data from Indexmundi (2015)

	Price ($US/tonne)		Mine production (kt)	
	2011	2014	2011	2014
Iron ore	168	97	2,940,000	3,220,000
Copper	8,823	6,863	16,100	18,700
Aluminium	2,400	1,867	44,400	49,300
Nickel	22,909	16,893	1,940	2,400

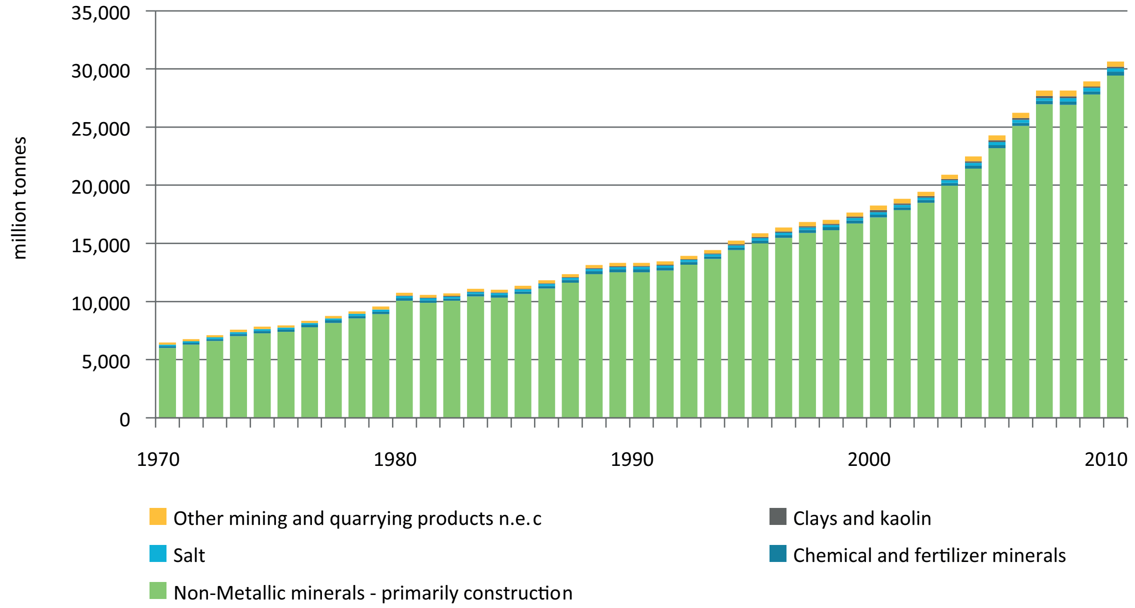


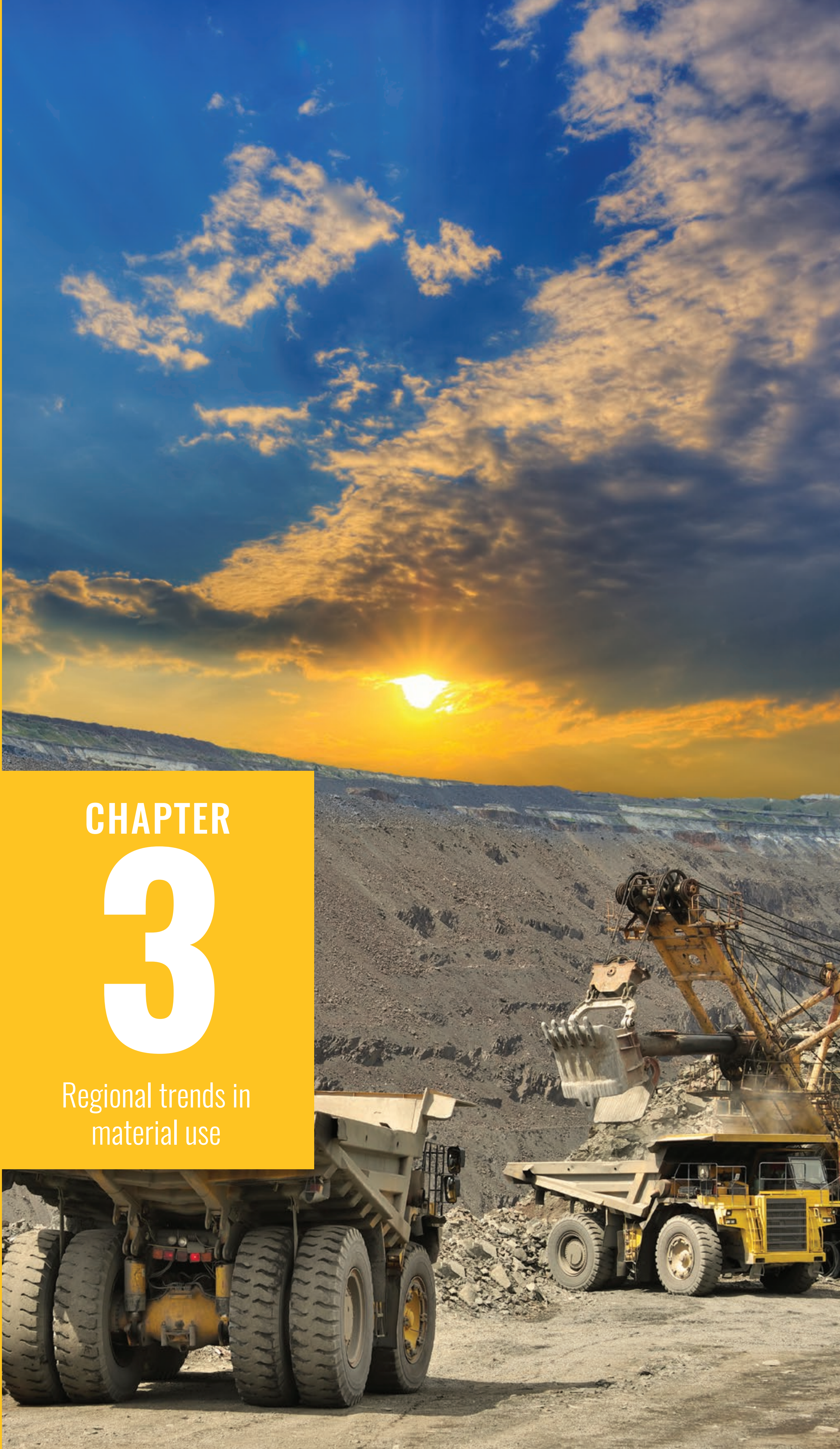
Figure 17. Global extraction (DE) of non-metallic minerals by material subcategories, 1970–2010, million tonnes

The data on DE of non-metallic minerals in Figure 17 are disaggregated into five categories and show clearly the domination of this category by construction minerals, in total tonnage terms. Not only was it one to two orders of magnitude larger than any of the other non-metallic minerals categories, it also grew at the fastest rate, 4.1% p.a. compounding from 1970 to 2010, compared to 2.6% p.a. for other mining and quarrying products n.e.c, the next fastest growing. At 29.5 billion tonnes in 2010, the subcategory of construction minerals was larger than any of the other complete materials categories (biomass, fossil fuels and metal ores). While extraction quantities were volumetrically huge, there is little prospect of World supplies becoming depleted in the foreseeable future as the category is largely composed of common rock, or crushed aggregates derived from rock.

At the local scale, however, supplies can be severely limited, or their extraction can cause unacceptable environmental damage. An example of the former situation is where settlements are on major alluvial flats or deltas with little or no rock exposed at the surface. In such cases, the rock-based aggregates crucial for concrete and road base may need to be replaced by firing alluvium to create bricks, which may then be crushed for use as aggregate. This practice is expensive, and the requirement for fossil or biomass fuel will typically be more environmentally damaging than the extraction of alluvium of itself.

Another situation where extraction of construction minerals can be highly problematic is where massive amounts of sand are extracted for land reclamation projects. In recent decades this has caused some political tensions between Southeast Asian nations. Finally, the extraction of natural sand from rivers and coasts in even modest amounts can be problematic due to both the environmental sensitivity of these areas, and their importance as sources of animal protein (in the form of fish) and of water, in the case of rivers.

While volumetrically small, the subcategory of most concern should probably be chemical and fertilizer minerals. This is due to the fact that it contains several components of vital importance to global food supplies, notably phosphorous and potash. In the case of phosphorous, there has already been concern raised in some quarters about “peak phosphorous” (Cordell, Drangert and White 2009), however this concern seems to be predicated on the misconception that currently defined reserves bear a meaningful relationship to ultimately recoverable resources. In the case of a relatively little explored-for commodity like phosphate, which nonetheless already has well defined reserves sufficient for many decades, there is little reason to believe in any such linkage. Increasing extraction and use of phosphorous is more likely to cause problems with the environment’s ability to “sink” artificially mobilized phosphorous and other fertilizers. The damage caused to aquatic ecosystems in particular by eutrophication is a demonstrable and current problem, and one that can be expected to increase as we attempt to feed a growing world population from a static land supply by intensifying inputs.



CHAPTER

3

Regional trends in material use

Regional trends in material use

Past economic development and the history of natural resource use have put different world regions on different trajectories resulting in different outcomes for material flows and material efficiency. The objective of this chapter is to explain these differences between seven major world regions. To do so, the chapter looks at material flows and interactions within and between seven large, multinational regions which together encompass the World. We distinguish between Africa; Asia and the Pacific; Eastern Europe, Caucasus and Central Asia (EECCA); Europe; Latin America and the Caribbean; North America; and West Asia.

The first section outlines where primary materials which underpin global economic activity are extracted, outlining trends in extraction over time and noting where major global events have left an imprint on regional extraction patterns.

The second section deals with trade in primary materials and the effect this has on the final distribution, availability and consumption of primary materials throughout the world. Two complementary indicators of trade in primary materials are used, the physical trade balance (PTB) and the raw material trade balance (RTB). The PTB focuses on the literal physical trade of materials, i.e. volumes that cross national borders as imports or exports. The RTB calculates the raw material requirements of direct traded commodities, i.e. the materials that were required to produce the traded commodities in the country of origin. The RTB includes indirect and direct material flows and adds them up to a raw material equivalent regardless of where the materials were physically invested in the production or where associated process wastes and emissions may accrue[5].

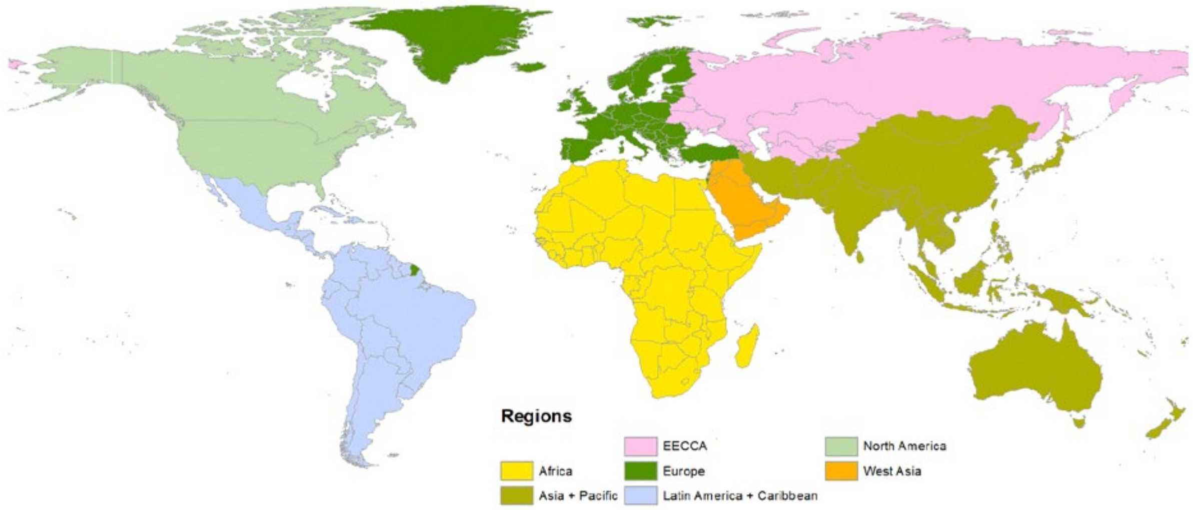


Figure 18. Regional classification used in this report

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[5] DE (Domestic extraction) and RTB (physical trade balance) use the same system boundary between economy and environment when natural resources are extracted and became a commodity that has a price attached.

The third and fourth sections deal with the analysis of where materials are consumed at the regional level, using a direct, territorially-defined metric for consumption (i.e. domestic material consumption) in section three, and a final consumption-based metric (material footprint of consumption) in section four. These two different measures are directly analogous to, and incorporate, the two different measures of trade introduced in section two.

Section five looks at the efficiency with which different regions convert primary materials into GDP. The two concepts of material consumption used in sections three and four are both used to produce alternative views of resource efficiency. A systematic divergence between the two alternative metrics for material intensity is identified, and its possible implications for dematerialization and Environmental Kuznets Curves (a hypothesized situation where various indicators of environmental degradation tend to get worse as modern economic growth occurs, until average income reaches a certain point) are briefly discussed.

Section six provides an overview of regional trends in population, GDP, domestic material consumption (DMC) and material footprint (MF) for each of the seven regions.

3.1 The origin of materials – domestic extraction in different world regions

Different parts of the world are endowed with different natural resources and some natural resources are more common than others which are only available in very few places. Most countries undertake agriculture of some kind but not every country has a large livestock sector which is often the case in countries that have vast, low productivity grasslands such as Argentina, parts of the United States and Australia. Some countries are rich in forests and host a timber industry while others have largely deforested. Fossil fuels are concentrated to some countries and regions and the same is true for many metals where for some metals we have a small number of producers which dominate world production. Non-metallic minerals such as sand and gravel are usually very common and quarrying of such materials is a common feature of almost every economy with a few exceptions of countries which have very little land available.

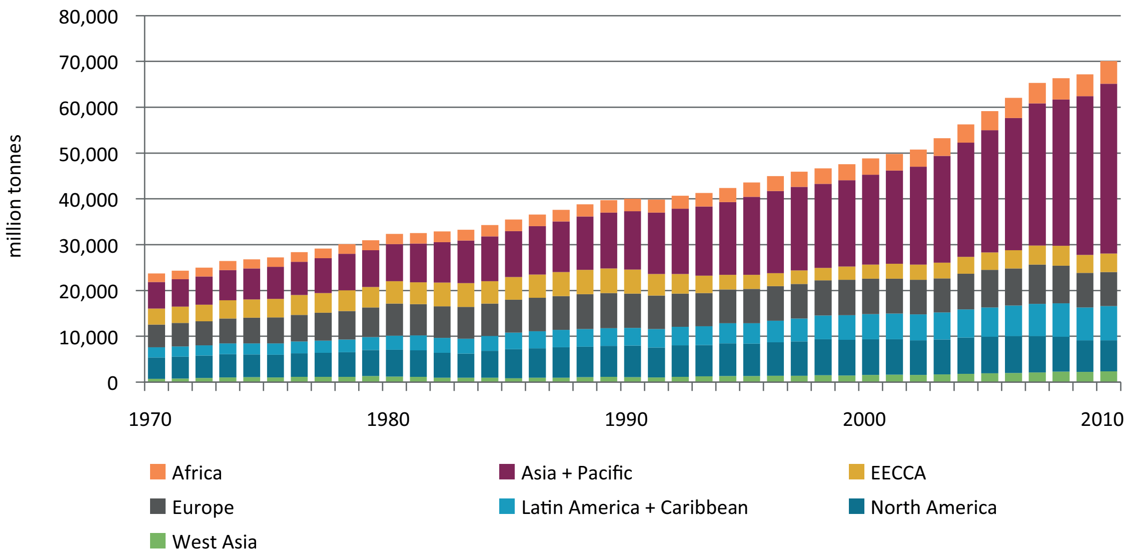


Figure 19. Domestic extraction (DE) by seven subregions, 1970–2010, million tonnes

Figure 19 shows the shares of seven world regions in global domestic extraction of materials. While global material extraction tripled between 1970 and 2010 (compare against Chapter 2) this growth was overwhelmingly driven by increasing domestic extraction in the Asia-Pacific region, which increased more than fivefold in just 40 years, at a compounding annual rate of nearly 4.8%. The average rate of growth actually increased in the latter half of the period (from 1990 to 2010) showing the acceleration of material extraction and demand from Asia and the Pacific. The Asia-Pacific region's share of global DE consequently more than doubled over the past four decades, from less than a quarter of the global total to more than half.

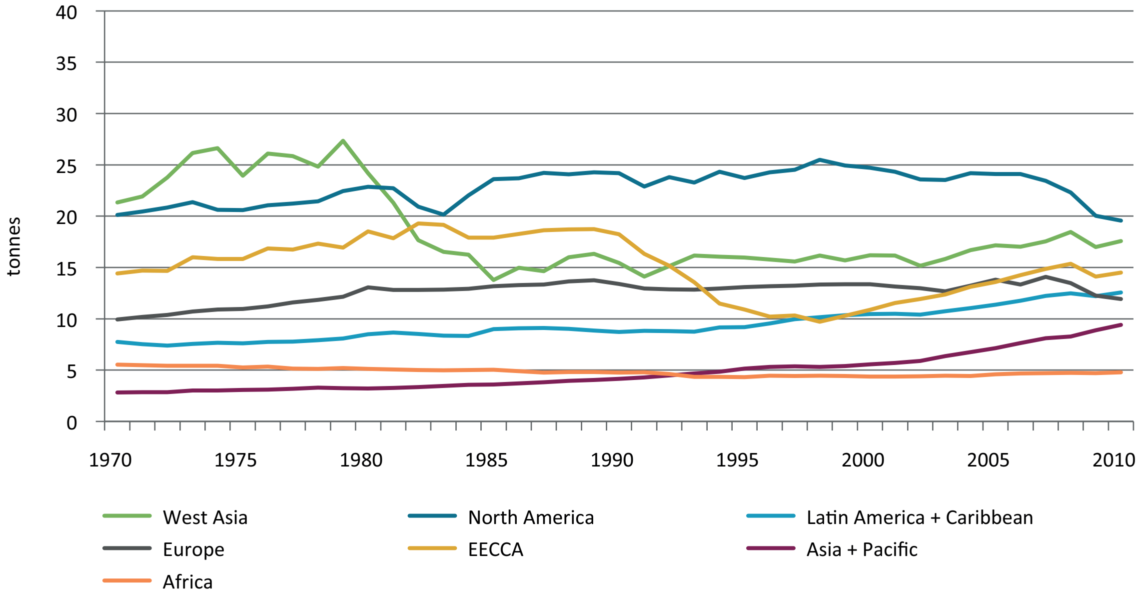
Table 4. Shares of global material extraction, 1970–2010

	1970	2010
Africa	7.9%	7.0%
Asia and Pacific	24.3%	52.9%
Eastern Europe, Caucasus and Central Asia	14.7%	5.8%
Europe	20.9%	10.5%
Latin America and Caribbean	9.4%	10.7%
North America	19.6%	9.7%
West Asia	3.2%	3.4%

The shares in domestic extraction of Africa, Latin America and the Caribbean and West Asia stayed relatively constant over the four decades but grew in total volume. Europe and North America experienced sharp declines in their global share of material extraction and so did Eastern Europe, Caucasus and Central Asia (EECCA) whose fall in share was most pronounced. While relative shares contracted for many regions, total domestic extraction of materials still grew in all cases, with EECCA being the only region which saw growth of less than 40% in DE over the period (the EECCA increase was 16%). Latin America, West Asia and Africa all saw growth in total DE of greater than 100%, at compounding annual growth rates of 3.1%, 2.9% and 2.5% respectively.

Some major economic events left clearly discernible impacts on the trajectory of DE. The reduction of West Asia's DE immediately after 1980 reflects decreased exports of oil in the wake of the second oil price shock, while North America's contemporaneous decline in DE is consistent with the economic recession which accompanied the oil price shock there. A major reduction in the EECCA region's DE can be seen over the 1990s, in the context of the economic dislocation following the break-up of the former USSR. More recently, the effect of the GFC on the DE of North America and Europe is clearly visible, as is the degree to which the impact of the economic downturn was muted in most other regions.

Figure 20. Per capita domestic extraction (DE) by seven world regions, 1970–2010, tonnes



In contrast to the growth seen in total DE for all regions, Figure 20 shows a much more mixed situation with regard to per capita DE, with three of the seven regions (Africa, North America and West Asia) showing at least marginal decreases between 1970 and 2010. The Asia-Pacific region shows very strong growth in DE per capita and this, combined with the region's large population, accounts for its dominance of global DE trajectories as seen in Figure 19. The declines in per capita DE for Africa and West Asia are of particular interest in that they show that despite the rapidly growing total DE for these regions displayed in Figure 19, their populations are growing even faster, effectively reducing the already low per capita domestic resource availability in Africa and West Asia. In the case of Africa, this reduction in per capita resource extraction starts from a low (and arguably inadequate) initial base. This is in contrast with the situation seen for West Asia, which came off the highest base of all regions and still ended the period at the second highest DE per capita level, despite a total decline of 18%. Latin America shows a steady increase, finishing the period over 60% higher, mostly caused by metal ores extracted for export. The extent to which this may reflect increases in external demand rather than domestic consumption is discussed below, with reference to more detailed data on the specific material components of DE.

Figure 21 shows details for the four specific material categories which make up total DE, on a per capita basis. Detail of the composition of the materials used by a society is important and can yield information on where a society is situated in the transition from an agrarian to an industrial society, and on the speed with which that transition is taking place. One important piece of information in this context is biomass inputs relative to mineral inputs. A high biomass share is indicative of a more agrarian economy, with mineral materials (encompassing fossil fuels, metal ores, and non-metallic minerals) increasing their shares as a society increasingly adopts the mineral-based energy and materials systems typical of industrial society (Fischer-Kowalski and Haberl 2007).

Figure 21 shows a very wide range in the proportion of domestic extraction (DE) of biomass between the different regions, and some markedly different trajectories. The Asia-

Pacific region stands out as the region which has most radically shifted away from biomass, which had a share of 53% of all materials in 1970, decreasing to just 22% by 2010. This is the second lowest share of DE for biomass seen for any region, lower even than the long industrialized regions of North America and Europe. The rapidity and degree of this change raises the question of whether the recent growth rates can be expected to decrease in the near future. While the Asia-Pacific region's per capita extractions of fossil fuels grew twofold and metal ores grew more than threefold, it was growth in non-metallic minerals (dominated by construction aggregates) which contributed by far the greatest share, increasing by over sixfold, a compounding growth rate of 5.1% per year over the past four decades, and of 6.5% per year over the most recent two decades. This is indicative of a very rapid build-up of long-lived infrastructure stocks, mainly in China. With DE of non-metallic minerals at over five tonnes per capita in 2010, the Asia-Pacific region was already approaching the levels seen for North America and Europe (6.4 and 6.2 tonnes per capita respectively), a level at which DE appears to stabilize (after transient levels as high as 9.6 tonnes per capita).

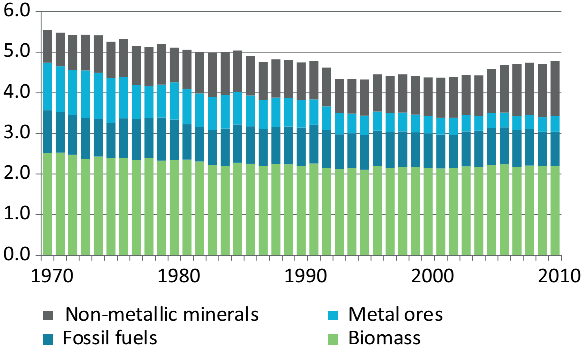
West Asia has both the lowest total per capita extraction of biomass and by far the lowest share, at 5% in 2010. DE in West Asia is an anomalous case in that DE is dominated by extraction of fossil fuels for export. The region saw its DE of non-metallic minerals increase from 4.6 tonnes to 7.6 tonnes per capita between 1970 and 2010, giving it the highest per capita DE in this category. Also, per capita exports of fossil fuel exports fell by over 40% over the period. DE of fossil fuels still accounted for some 52% of West Asia's total DE in 2010.

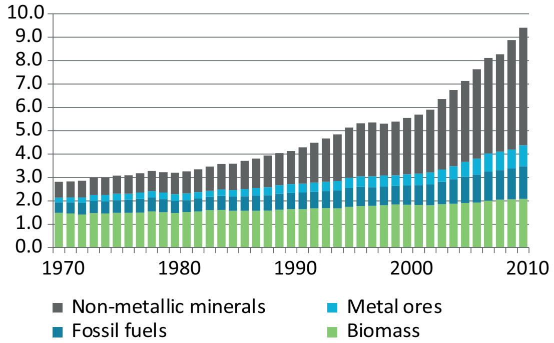
Latin America saw growth in DE per capita of all categories of materials over the period, with least growth in fossil fuels (20%) and greatest in metal ores (139%). It saw a significant decline in the share of biomass from 52% to 43%. However, this is still high by global standards, exceeded only by Africa, where biomass accounted for 46% of materials extraction in 2010; a slight increase on the 45% share in 1970. It is noteworthy that this slight increase in Africa of the share of biomass happened despite a fall (of 13%) in total per capita DE of biomass in Africa. This means that not only are the basic commodities necessary to maintain even an advanced agrarian level of development becoming more, rather than less, important in Africa but that local extraction is providing less of these materials per capita. Africa also saw decreased per capita DE of fossil fuels and metal ores, however there was quite strong growth (70%) in non-metallic minerals, which even so remained very low by World standards, at 1.35 tonnes per capita (45% lower than Latin America, the next lowest in this category).

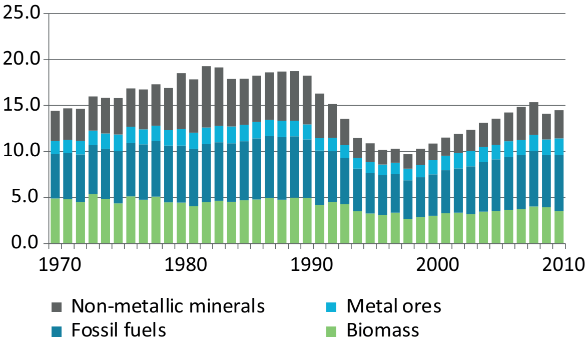
Levels of per capita DE for fossil fuels and metal ores declined in both Europe and North America, while biomass and non-metallic minerals both increased. In both cases the changes were notably gradual, with none of the explosive growth or occasional dramatic contractions seen for some of the other regions. This is a sign that these regions have already passed through the most volatile stages of the socio-metabolic transition (from a material flows perspective) and have settled into a more stable pattern of material consumption. While the trajectories of DE for these two regions are relatively stable, the extremely low levels of DE per capita in Europe for metal ores, lower even than for Africa in 2010, make clear that domestic metal extraction in Europe is not providing anywhere near the metal inputs required to support the material standard of living enjoyed by the average European. For that we need to take into account the additional supplies of primary materials obtained through trade. For this we turn to the physical trade balance data presented in Figure 26.

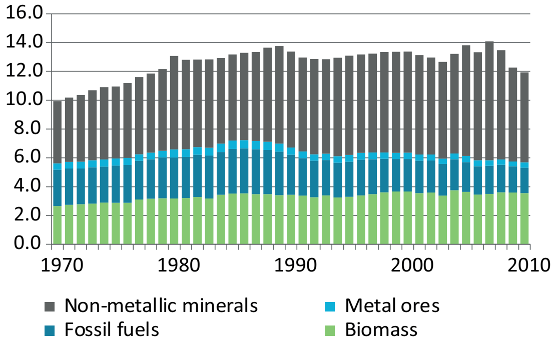
Figure 21. Per capita domestic extraction (DE) in 7 world regions, 1970–2010, tonnes per capita

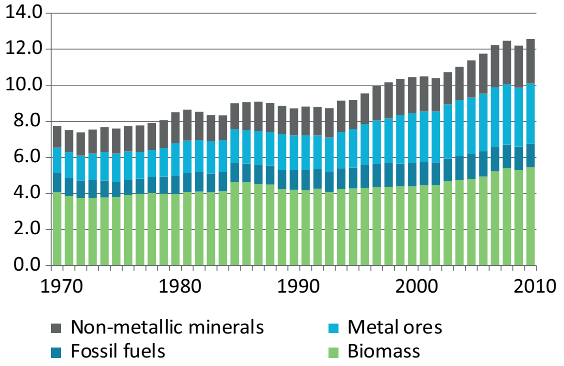
3.2 Trade in materials

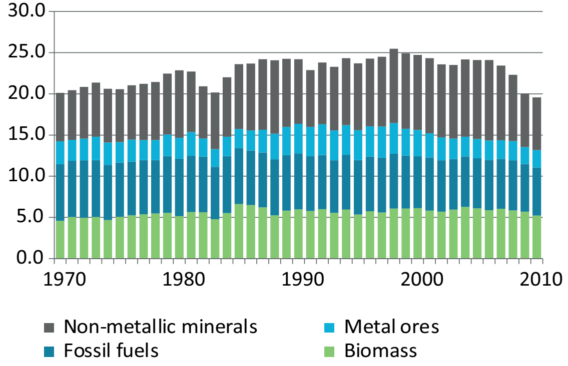

Regional domestic extraction per capita, by material category - Africa

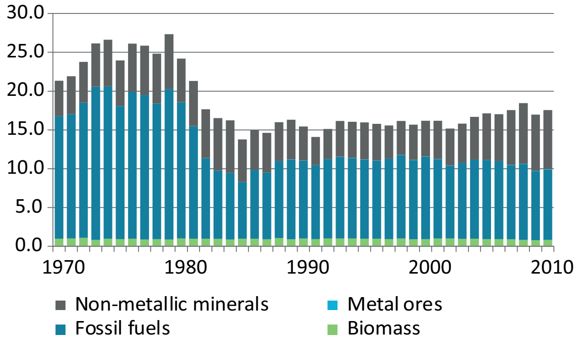

Regional domestic extraction per capita, by material category - Asia & Pacific


Regional domestic extraction per capita, by material category - Eastern Europe, Caucasus & Central Asia


Regional domestic extraction per capita, by material category - Europe


Regional domestic extraction per capita, by material category - Latin America & Caribbean


Regional domestic extraction per capita, by material category - North America


Regional domestic extraction per capita, by material category - West Asia

Trade occurs because of specialization and division of labour, which in most countries are concentrated on a specific aspect of production, trading for other products. While some production is fairly generalizable across countries, other types depend on very specific location factors including natural resource endowment, availability of skilled labour, institutional arrangements, and taxation and government subsidies that favour specialization in different aspects of resource extraction, and manufacturing perhaps based on a comparative advantage (perceived or real) in the production of some tradable commodity.

Figure 22 shows the course of the total physical trade balance (physical imports – physical exports) for the seven regions combined[6]. Positive numbers indicate that a region has been a net importer, negative numbers indicate a net exporter. The lion's share of traded materials will fall to primary materials such as coal, oil, gas, iron ore, wheat, meat and dairy, and timber which in total make up 90% of all traded commodities. Semi-manufactures and final goods, while creating most of the trade value, are small in overall volumes and comprise around 10% of all physical traded tonnes of materials.

A clear pattern in physical trade can be seen where all regions tend to remain either a net exporter or net importer over time, with the exception of North America which has changed roles for some periods but which nonetheless could be characterized as typically being a net importer albeit of small volumes. Europe has been the World's major net importer for virtually the whole period. The only year where this was not the case was 2009, in the immediate wake of the GFC, where the Asia-Pacific's dependence on net imports slightly exceeded the considerably reduced demand from Europe. The Asia-Pacific region has however shown by far the most rapid and consistent growth in its requirement for imports, which increased more than fourfold between 1970 and 2010 at a compounding rate of 4.4% per year, and 6.5% per year over the latter two decades. In contrast, Europe's total net imports only increased by 50% over the full period. The high ongoing dependence of Europe on net physical imports indicates how it has been able to maintain high material living standards while having levels of DE of some key material categories at or below the levels of less wealthy regions.

West Asia maintained major net exporter status over the full period, but its relative importance declined as it moved from being the World's largest net exporter in 1970 to second largest by 2010, with total net exports increasing by 35% in total. The profile of West Asia's physical trade balance (PTB) is interesting as it clearly shows the effects of the second oil price shock from 1980, echoing the effects seen previously in DE. Latin America shows relatively consistent growth in its net exports over time, which increased by a total of 164%, a compounding rate of 2.5% p.a. By far the fastest apparent growth in net exports was for the EECCA region, where exports grew at 5.0% per year. However, this figure will have been strongly boosted by the political changes in 1991, with trade which had previously been taking place intrastate (within the USSR) being reclassified as international trade. Even so, the increase in net exports since the dissolution of the USSR has still been extraordinarily rapid, such that by 2007 it exceeded West Asia for the first time. Africa remained a net exporter for the entire period, with a marginal increase (18%) in total tonnage between 1970 and 2010.

Figure 22. Physical trade balance (PTB) by seven subregions, 1970–2010, million tonnes

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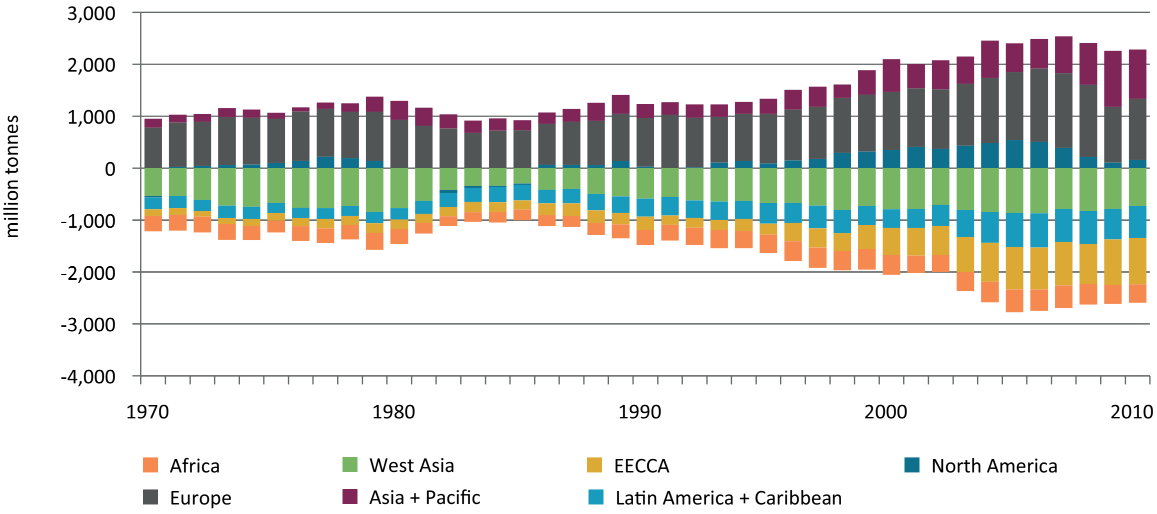
[6] Net imports and net exports in this graph frequently do not balance. This due to discrepancies in the base data set i.e. exports do not reconcile exactly with imports in the United Nations Comtrade database, on which these PTB accounts are largely based. While these differences are only minor compared to total trade (equal to around 3% of total imports in 2010), the relative importance of any difference gets greatly magnified when viewed in the context of PTB, as the vast bulk of imports and exports cancel each other out, but any discrepancy is fully preserved.

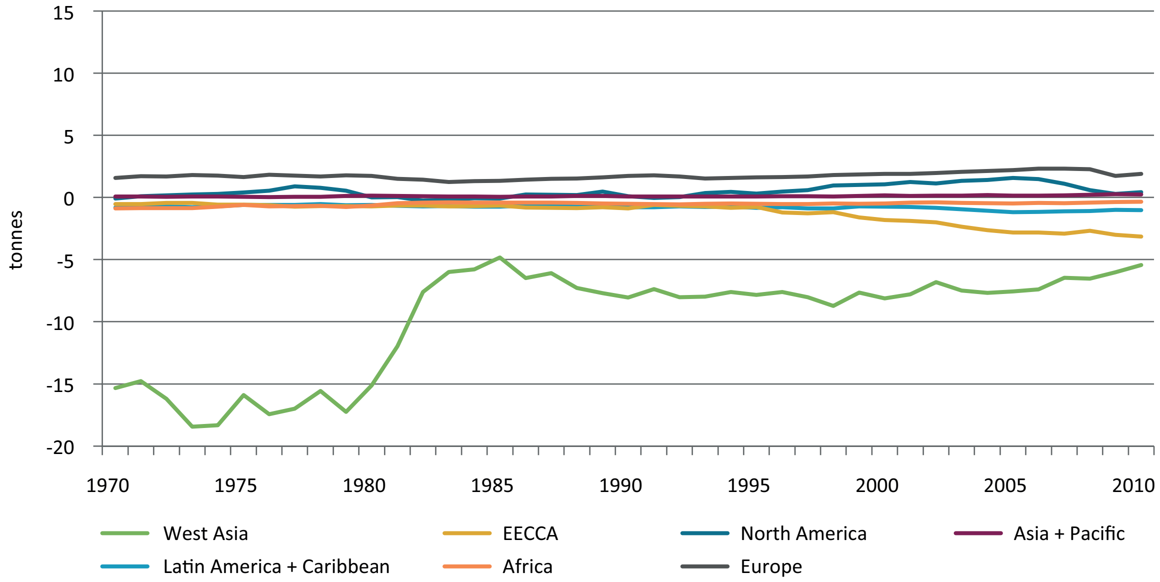


In Figure 23 we can see that West Asia is no longer the largest net exporter in total tonnage. West Asia's per capita exports decreased 65% over the period, with 5.4 tonnes per capita in 2010. This was still more than 70% higher than in the EECCA region, which was the second largest net exporter in 2010. The rapid increase in EECCA net exports is very apparent from 1995, coinciding with the period of recovery after the massive economic dislocations accompanying the dissolution of the USSR.

Viewed on a per capita basis, the very high relative dependence of Europe on imports is even clearer than it was in Figure 22 being over four times higher than the next, North America, and nearly eight times that of the Asia-Pacific region, which we saw in Figure 22 was the second most import dependent region in total tonnage terms. Three of the seven regions had net imports/exports of less than 0.5 tonnes per capita (North America, Africa and the Asia-Pacific), which may imply near self-sufficiency when compared to the much higher per capita values for DE in Figure 20. It must be noted, however, that primary materials are often traded in much more concentrated form than they are extracted, and so traded primary products are frequently of much greater value to an economy than an equivalent tonnage of DE. This phenomenon is particularly pronounced for metal ores, but is also significant for biomass (Schandl and West 2012).

Figure 23. Per capita physical trade balance (PTB) by seven world regions, 1970–2010, tonnes

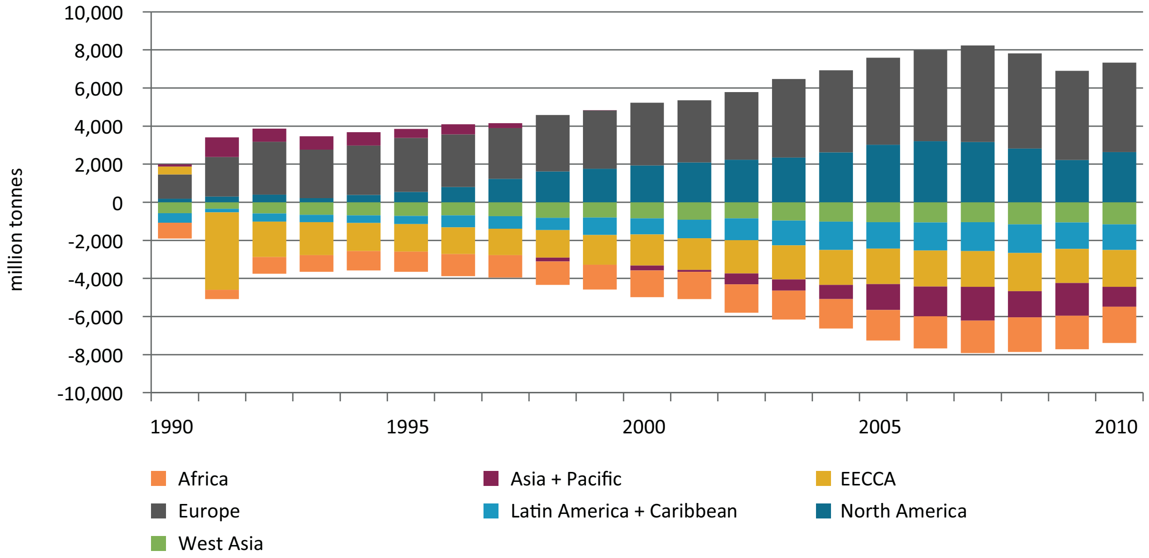
A measure which largely compensates for this concentration of primary commodities prior to trade is raw material equivalent (RME), one



of a family of metrics obtained by using multi-regional input-output (MRIO) tables with satellite material flow accounts. The RME-based equivalent of PTB is the raw material trade balance (RTB), which takes into account the upstream material flows involved in producing a tonne of exported product, rather than just the tonnage of the product itself. For this study a time series covering the years 1990 to 2010 was produced using the global, multi-regional input-output framework Eora developed by the University of Sydney (Lenzen et al. 2013) and a new global material extraction satellite data set detailing 42 material extraction categories for every country in the world. Standard input-output analytical procedures based on the conceptual framework developed by Leontief (1974) were applied. The results for RTB are shown in Figure 24.

Figure 24. Raw material trade balance (RTB) by seven subregions, 1990–2010, million tonnes

Comparing Figure 24 to the preceding PTB-based figures, one obvious feature is the large increase in total tonnages attributable to trade when upstream flows are taken into account, with net exports in 2010 of 7.4 billion tonnes on the RTB metric, as compared to 2.6 billion



tonnes for PTB. In addition to the major change in magnitude, there have also been some very major changes in net importer/exporter status. While Europe has maintained and increased its relative share and dominance as the world's major importer of primary materials, the Asia-Pacific region shifts from being the second largest importer to a marginal net exporter. The main reason for this is that many of the primary resources apparently consumed in the Asia-Pacific region are actually used to produce manufactured goods for export. North America also figures as a much more significant importer of raw materials relative to Europe. The RTB metric effectively captures this "embodiment" of resources in a region's exported products, and adds it to its export account. To illustrate further, where the PTB metric would typically only add one tonne to a region's export account for each tonne of aluminium it exported, the RTB will also capture the coal and gas used at various stages to produce that aluminium from bauxite, and some of the materials used to make the plant in which the aluminium was produced, etc. Crucially, it will also capture much of the mass of the original bauxite as initially extracted[7].

Among the net exporters in Figure 24, the relative importance of West Asia has decreased greatly when compared to the PTB-based figures, while Africa moves from being the least significant net exporter to the most significant. Growth in Africa's net exports is also much higher on the RTB metric, increasing by 127% over the period 1990 to 2010. The EECCA region remains the second most significant net exporter in Figure 24, but its rate of growth is much slower and more stable than seen previously for PTB[8]. For Latin America and the Caribbean, the pattern for RTB is similar to that seen for PTB, although the rate of growth in RTB from 1990 to 2010 was much faster, 5.2% p.a. compounding as compared to 2.9% over the same period for PTB. The change in status from net importer to net exporter seen for the Asia-Pacific region roughly coincides with the rise of China as the major manufacturing nation in the region. Prior to the start of the

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[7] The extent to which it succeeds in fully accomplishing this is an area for further research. In the course of using material footprints for this and other reports and research papers, examples have come to light where the levels of consumption indicated for some materials and countries, while much better than PTB, and still appear to be too high. Specific cases are metals consumption for Chile and Australia. One likely factor is the use of constant commodity prices regardless of whether that commodity is used intra- or inter-sectorally, as discussed in Weisz and Duchin (2006).

[8] The extreme volatility for the years 1990–1991 is likely to reflect problems with base statistics, and with compatibility of jurisdictions for which statistics were compiled, during the dissolution of the USSR.

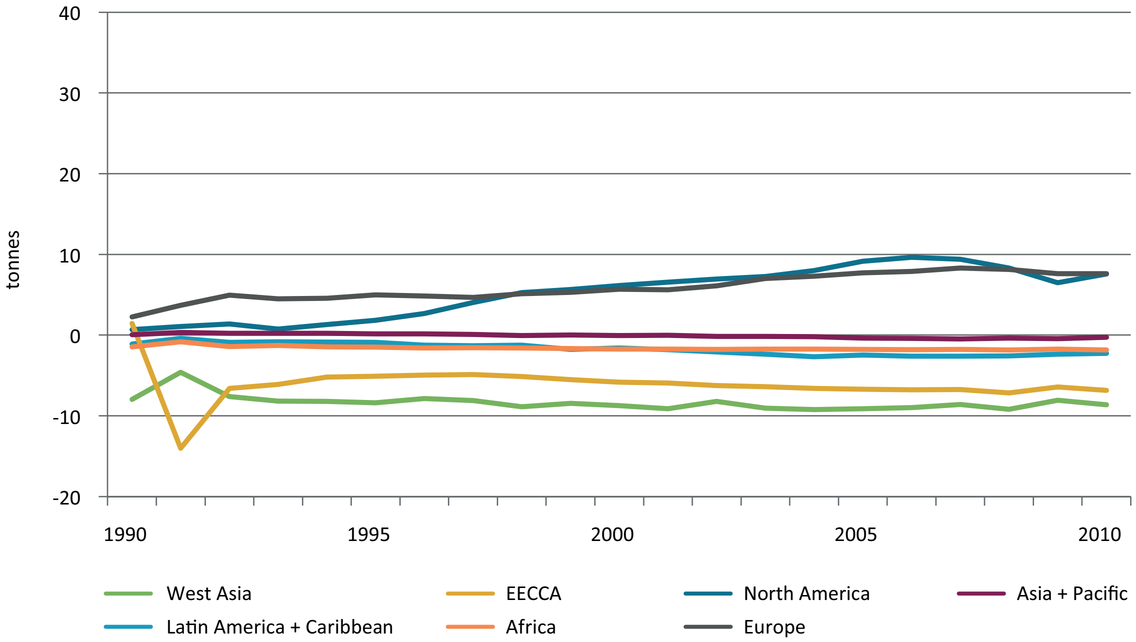


Figure 25. Per capita raw material trade balance (RTB) by seven subregions, 1990–2010, tonnes

new millennium, the economy of the region as a whole was dominated by a mature industrialized country, economically similar in many ways to North America and Europe, and this appears to be reflected in RTB over this period. From 2000 on, it was the rapidly industrializing economy of China which increasingly dominated, with the region's RTB profile subsequently shifting to resemble that of developing regions.

The similarities between Europe and North America regarding RTB characteristics become even more pronounced when put on a per capita basis, as in Figure 25. Both ended the period with near identical RTB net imports of 7.6 tonnes per capita, after two decades of growth from bases in 1990 of 2.3 and 0.7 tonnes per capita for Europe and North America respectively. Both peaked between 2006 and 2008. The growth profile seen would be consistent with both regions progressively outsourcing many of their materials- and energy-intensive industrial processes to other regions. West Asia, followed by the EECCA region, are by far the greatest net exporters on a per capita basis, with a much closer concordance between the two for RTB per capita than seen for PTB. The trajectories of Latin America and Africa are very similar over time, with both being moderate net exporters and both increasing in per capita terms. The Asia-Pacific region is noteworthy for how small net trade flows have remained on a per capita basis, always less than 0.5 tonnes per capita whether net imports or exports.

In Figure 26 we return to the PTB metric, in this case giving more detailed disaggregation by the four main material categories, on a per capita basis. A first insight from an overview of Figure 26 is the dominance of fossil fuels in net physical trade terms. Regions tend to start out and remain major net importers or major net exporters for the full time period. In all cases except Latin America, fossil fuels are clearly the major net import/export item in volume terms. For Latin America, net exports of metal ores are frequently larger than fossil fuels. Europe and North America have consistently been major net importers of fossil fuels, although the trajectory for North America is notably more volatile, probably reflecting that region's greater ability to satisfy domestic demand from

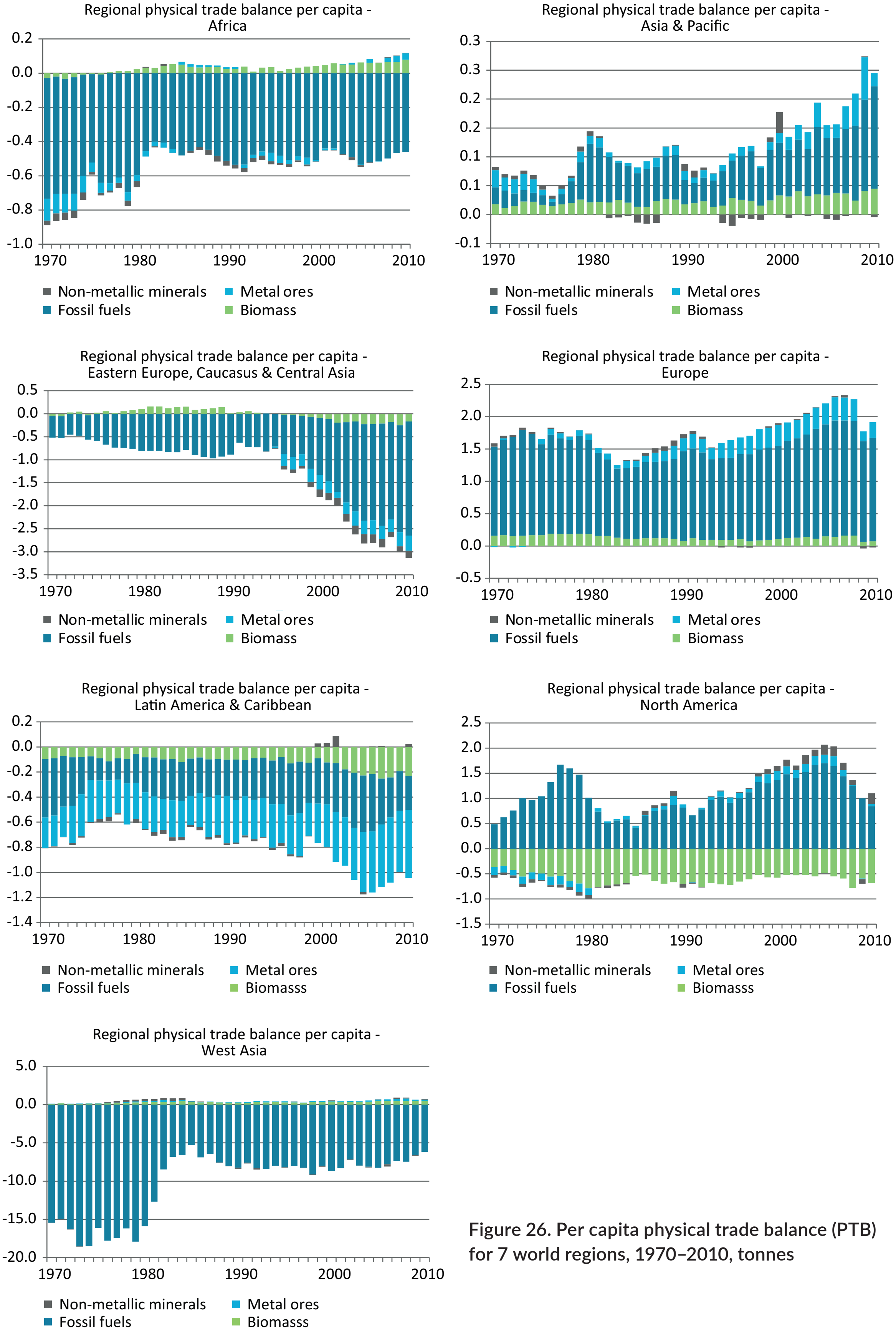


Figure 26. Per capita physical trade balance (PTB) for 7 world regions, 1970–2010, tonnes

local extraction whenever oil prices become sufficiently high. The Asia-Pacific has also remained a net importer, but at per capita levels an order of magnitude lower than Europe. Africa, EECCA, Latin America and West Asia have been consistent net exporters of fossil fuels, with West Asian levels an order of magnitude or more higher than the other regions over much of the period. In recent decades, net exports of fossil fuels from the EECCA region have reached 40% of the level of West Asia, due to a combination of major increases in the former and contraction in the latter.

With regard to other materials categories, the relatively large net imports of metal ores by Europe are notable, and show fairly strong and consistent growth until the GFC. This indicates how the high material standards of living in this region are maintained despite the very low DE of metal ores noted in Figure 19. It should again be remembered that for metal ores in particular, a unit of traded material is likely to be equivalent to many tonnes of DE, due to concentration prior to trade. A contrast to high European imports of metal ores can be seen in Latin America's high net exports. A third feature which stands out in Figure 26 is the very large net exports of biomass from North America, by virtue of which it is the one region which shows some modest level of symmetry between its net imports and net exports, with biomass exports of similar magnitude to (mainly fossil fuel) imports in some years. All other regions are very heavily skewed towards being net importers or net exporters, although absolute levels per capita remained very low for the Asia-Pacific region until the new millennium.

A feature notable by its absence in Figure 26 is significant trade in non-metallic minerals. In almost all cases it is relatively small and also unusually prone to changing from being a net export to a net import of a region over time, in some cases multiple times e.g. for the Asia-Pacific region, Europe and Latin America. The low level of trade in non-metallic minerals can be explained by the category being dominated by construction aggregates. These are commonly available in most regions, in the required quantities, at very low unit prices. Low unit prices mean they are unlikely to be traded over significant distances. This consistent low level of non-metallic minerals trade as measured by PTB contrasts strongly with what we see when we use the RTB metric instead, in Figure 27.

The detailed four material category disaggregation of RTB in Figure 27 gives a different perspective on trade flows once the embodiment of raw materials is taken into account. At an overview level, a major difference is the greatly reduced dominance of fossil fuels, although they remain important. A second

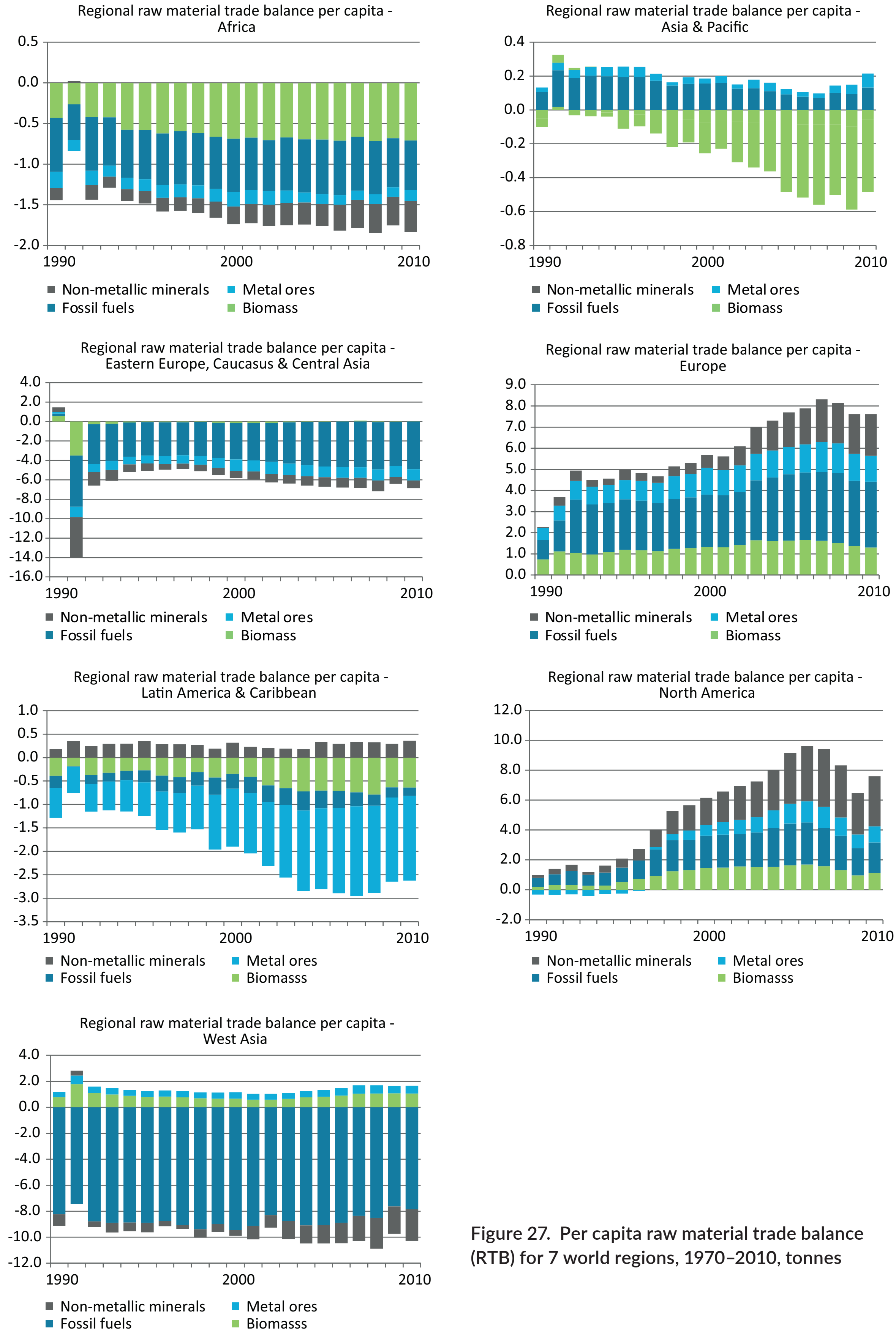


Figure 27. Per capita raw material trade balance (RTB) for 7 world regions, 1970–2010, tonnes

major difference is the increased importance of non-metallic minerals, and the much greater consistency they show as either a characteristic net import or net export of a region. With regard to individual regional profiles, the Asia-Pacific region becomes a major net exporter of both non-metallic minerals and of biomass, once the embodiment of these materials is taken into account. The result for non-metallic minerals in particular is consistent with a major build-up of manufacturing plants in China, much of it geared towards export markets. These embodied non-metallic minerals are reflected in the accounts of destination regions, most notably Europe and North America, which are major net per capita importers of all four categories of materials for the entire period, with the minor exception of metal ores from North America in the early to mid-1990s. For Europe, we also see net imports of metal ores averaging around four times higher on an RTB basis than we saw for PTB, while the factor for biomass is even higher (12 times). The factor for fossil fuels is much lower, at around 1.7, being consistent with both lower degrees of concentration in trade for fossil fuels and also with a large portion of the fossil fuel footprint being accounted for by final consumption locally. One perhaps surprising result is North America's change from a major net exporter of biomass on a PTB per capita basis to a major importer on an RTB basis. Africa becomes a net exporter of all materials, with biomass per capita increasing to comparable levels comparable to fossil fuels. Africa also becomes a net exporter of non-metallic minerals, at comparable levels to those seen for the Asia-Pacific region. This is an interesting result in that it seems unlikely to originate from major investment in manufacturing infrastructure for export.

Latin America's pattern is consistent with what one would expect to see for a region which exports large quantities of primary materials and simply transformed manufactures, in exchange for imports of elaborately transformed manufactured goods. It has net imports of non-metallic minerals embodied in imports from extraterritorial manufacturing infrastructure. Perhaps the least changed profile is that of West Asia, due to the overall dominance of fossil fuel exports there. There is nonetheless significant embodiment of non-metallic minerals which was absent from PTB, probably reflecting the large sale industrial and transportation infrastructure associated with major petroleum extraction for export and petrochemical industries.

3.3 Territorial (direct) material use

Domestic extraction of materials and the physical trade balance, when added up, result in the volume of materials managed on a national territory. This is the amount which needs to be transported and ultimately will become waste or emissions, though sometimes with a long time lag as for construction materials embodied in buildings.

Figure 28 shows the trajectory of the seven regions on the indicator of domestic material consumption. This indicator is designed to capture the territorial consumption of primary materials, whether they be sourced from domestic extraction or imported. Reference back to Figure 19 for domestic extraction will show that overall, the two indicators are very similar, as would be expected because PTB is usually an order of magnitude, or more,

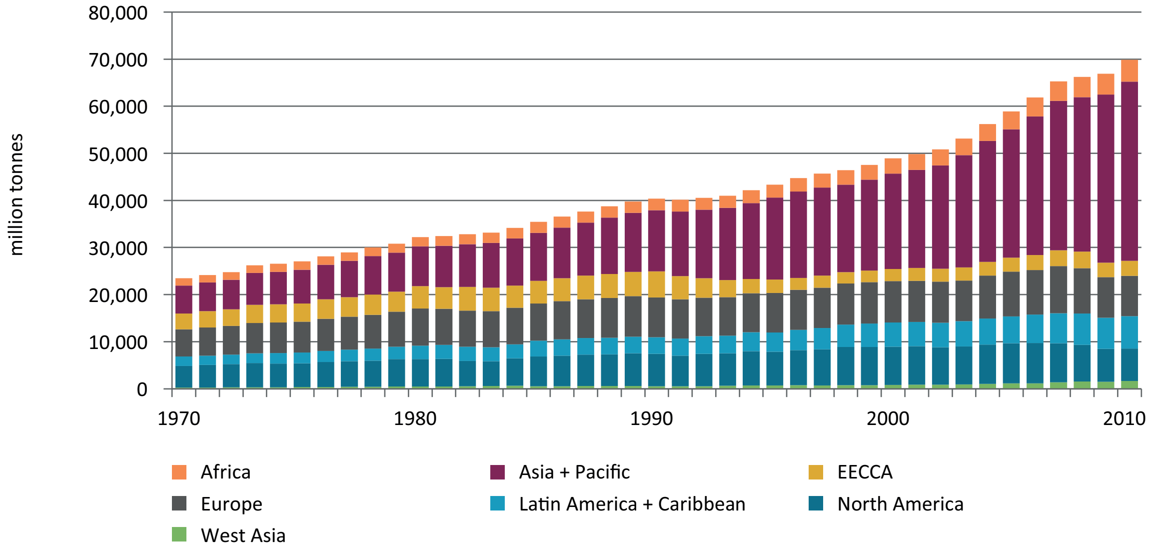


Figure 28. Domestic material consumption (DMC) by seven subregions, 1970–2010, million tonnes

smaller than DE. The main exception is where a region exports or imports large quantities of commodities which undergo little concentration prior to trade. In that case, the addition of PTB will significantly reduce or increase DMC compared to DE. For the seven world regions, the DMC differs most significantly from DE for West Asia, which for some years has a DMC 71% less than DE. This reflects that region's economic focus on the extraction of fossil fuels destined for export, commodities which retain much of their extracted volume in their exported form. All other regions maintained DMC volumes within +/–22% of their DE, the largest variations outside of West Asia being for –22% for EECCA (another major fossil fuel exporter) and +17% for Europe, with its high dependence on imported fossil fuels. In all other cases, total DMC was within 11% of DE.

Comparing Figure 30 to Figure 20 confirms the similarity between total DE per capita and DMC per capita for most regions. The only significant change in profile was for West Asia, where DMC is much more stable over time than DE, perhaps reflecting the much greater discretion OPEC nations had in curtailing extraction for export as opposed to that used to maintain the normal operation of the domestic economy. The profiles

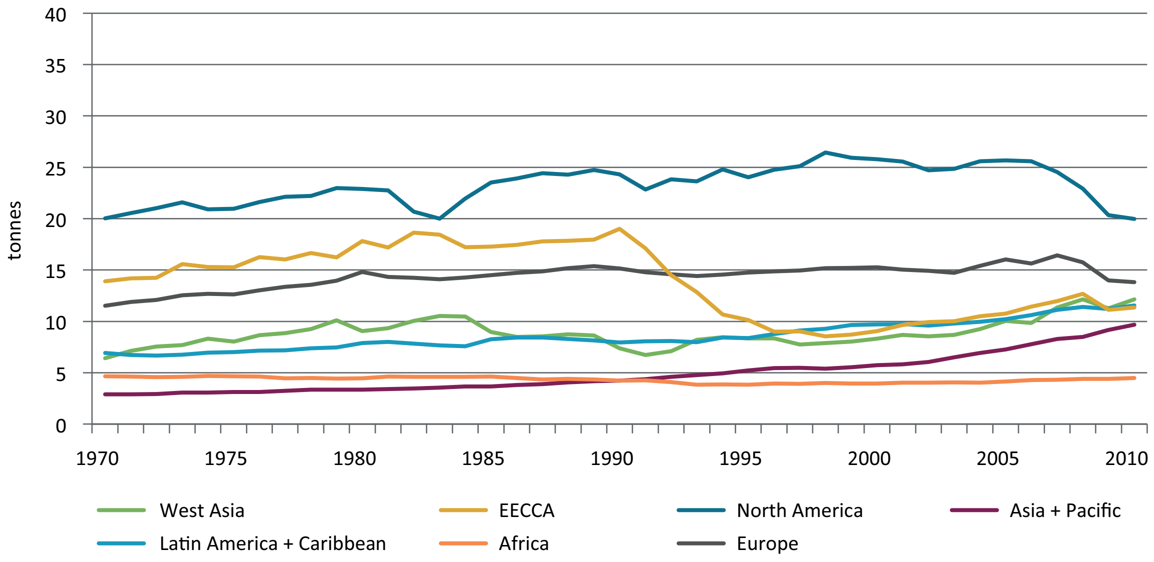


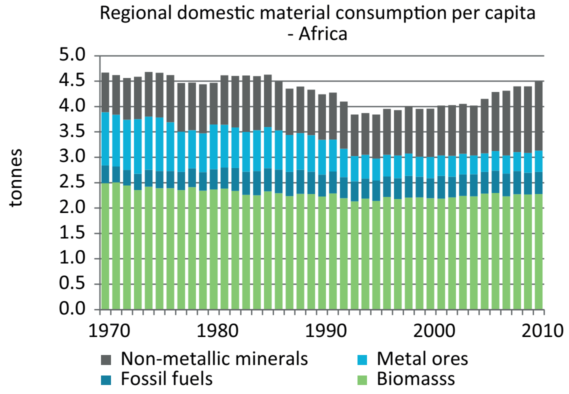
Figure 29. Per capita domestic material consumption (DMC) by seven subregions, 1970–2010, tonnes

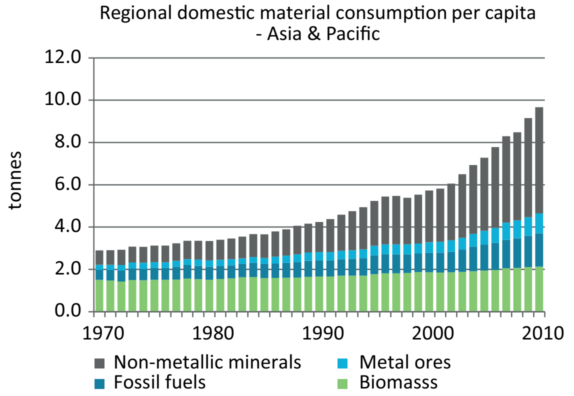
for EECCA and Europe were largely limited to translation of the curve up or down, rather than fundamentally altering the overall form.

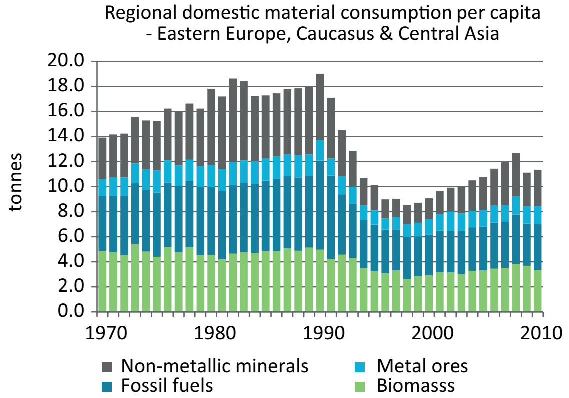
The four category disaggregation of materials for regional DMC in Figure 30, when compared to its counterpart for DE in Figure 21, again illustrates a general similarity between DMC and DE in most cases, and makes clear where occasional major differences arise. The huge reduction in West Asia's DMC of fossil fuels compared to DE is particularly clear, leaving DMC of non-metallic minerals by far the largest item of domestic consumption. The other clear regional differences seen are a major reduction in DMC of fossil fuels for Africa when compared to DE, and the reverse situation for Europe. All other regional profiles show little fundamental difference. The main use of Figure 30 will be for later detailed comparison with Figure 34, which uses the material footprint metric.

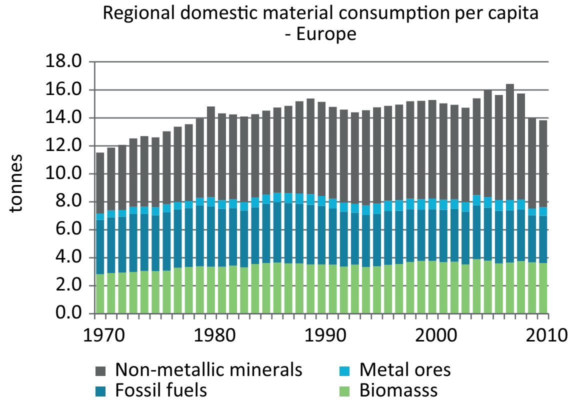
3.4 Material consumption

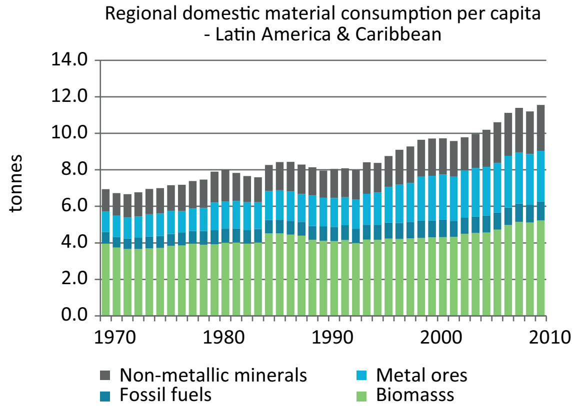
In this section the metric used for consumption is material footprint (MF), one of the measures derived using the Eora global, multi-regional input-output framework developed by the University of Sydney (Lenzen et al. 2013).
In common with RME, discussed in Section 3.2 above, MF takes into account upstream material flows involved in producing products,

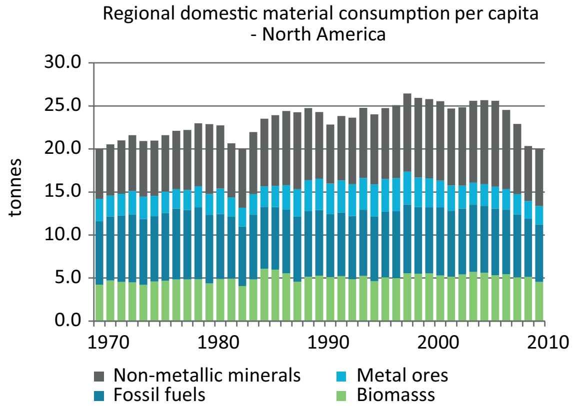

Regional domestic material consumption per capita - Africa


Regional domestic material consumption per capita - Asia & Pacific


Regional domestic material consumption per capita - Eastern Europe, Caucasus & Central Asia


Regional domestic material consumption per capita - Europe


Regional domestic material consumption per capita - Latin America & Caribbean


Regional domestic material consumption per capita - North America

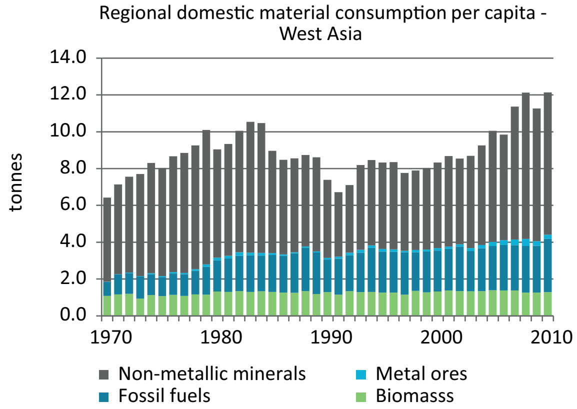

Regional domestic material consumption per capita - West Asia

Figure 30. Per capita domestic material consumption (DMC) by region, 1970–2010, million tonnes

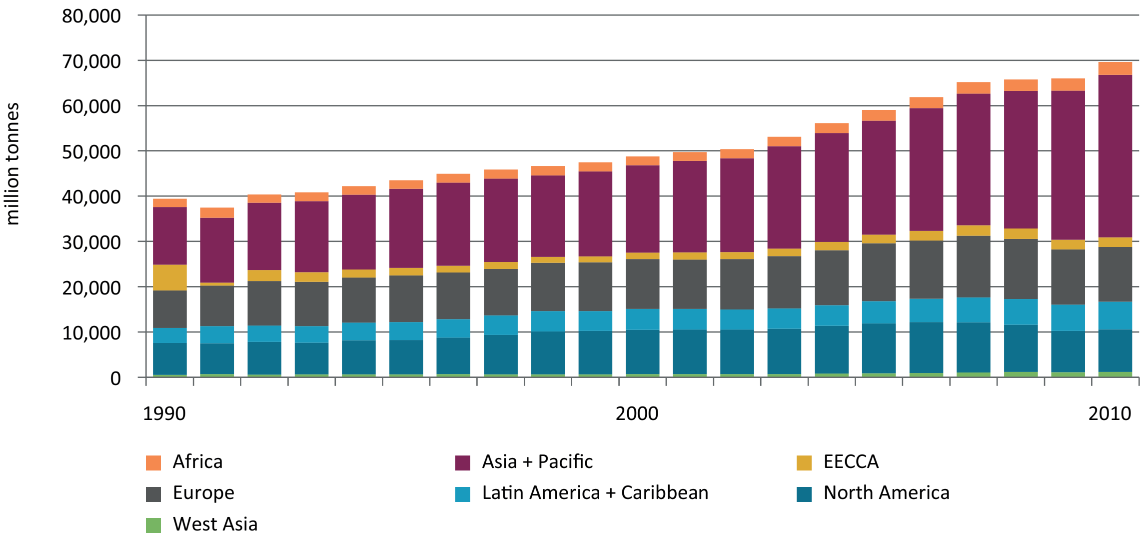
rather than just the tonnage of the product itself. In doing this it provides a far superior indicator of where responsibility for final consumption of primary materials is located. On the other hand, its linkage to where extractive and processing pressures actually accrue is much more tenuous than the DMC and DE measures. For a comprehensive analysis of where the costs and benefits associated with global material flows accrue, MF should thus be seen as complementary to the older indicators rather than as an alternative.

Figure 31 shows total MF by region for 1990 to 2010. The total over all regions will be the same as DE and DMC[9], but comparison with Figure 28 shows that the distribution of materials consumption among different regions can change quite radically.

Figure 31. Material footprint of consumption (MF) by seven world regions, 1990–2010, million tonnes

Figure 32. Variation of material footprint from domestic material consumption, 1990–2010

Ignoring the anomalous years of 1990–1992 for the EECCA region, in that region we find the largest consistent difference between direct territorial consumption, as measured by DMC, and consumption allocated by MF, with MF never more than 69% of than DMC, ranging to as low as 54% of DMC in 1998, with a median for the 17 years considered of 60%. This means that



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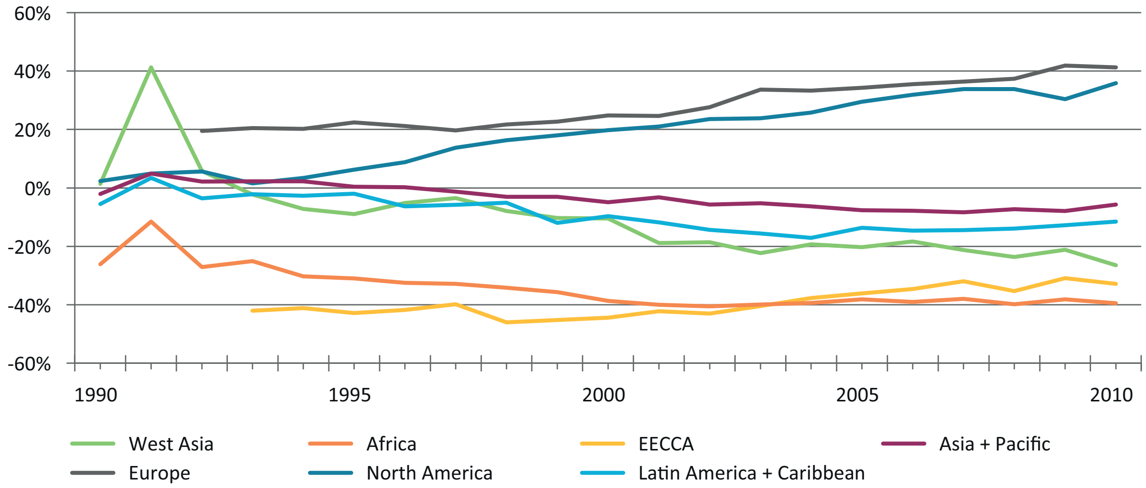
[9] While DE and MF should be strictly equal, minor differences between them and DMC will occur for due to the data inconsistencies in trade data discussed in section 3.2.



for most years, real final consumption in the EECCA region is less than three fifths what we would conclude from DMC. Another region where DMC appears to greatly overstate final consumption is Africa, where MF is less than 62% of DMC in most years. Outside of these two regions, the median variation of MF from DMC is 25% or less. For North America, and for Europe from 1992, MF consistently indicates higher levels of consumption than DMC, with most years 25% or greater for Europe and 20% or more for North America. For both regions, there is a clear trend over time towards MF estimating increasingly high relative to DMC. West Asia usually has MF lower than DMC, but is notable for beginning the period with MF estimating slightly high[10] relative to DMC, then declining steadily so that by the end of the period MF was consistently 20% or more lower than DMC. The closest agreement between MF and DMC over time was for the Asia-Pacific region, with MF usually estimating slightly lower than MF on average, but always remaining within a narrow (13%) band. The overall pattern for which regions MF over- and underestimates relative to DMC suggests a linkage with apparent relative decoupling i.e. some regions associated with decoupling also tend to be characterized with an upward trend in MF: DMC ratio. This is what we would expect to see if much relative dematerialization is achieved simply by outsourcing materials and energy-intensive stages of production.

Comparing the trajectories and levels of per capita MF in shown in Figure 32 with those shown previously for per capita DMC in Figure 29 reflects the regional differences between MF and DMC described above. Overall, the regions which had the highest DMC per capita (North America and Europe), have even higher MF per capita. Furthermore the trends for MF per capita over the past two decades show either less of a decline compared to DMC per capita, (North America) or a modest increase as opposed to a modest decrease (Europe). Those regions which had the lowest DMC per

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[10] The year 1991 is anomalous in West Asia's MF account, and somewhat so in Africa's. This anomaly for West Asia has been attributed to the First Gulf War (pers. comm. with M. Lenzen). Detailed country level data reveals that Africa's anomalous 1991 is attributable mainly to two major oil exporters there (Nigeria and Angola), while in Latin America Venezuela also shows a similar anomaly, suggesting that a Gulf War effect impacted the MF accounts of major oil exporters more generally.

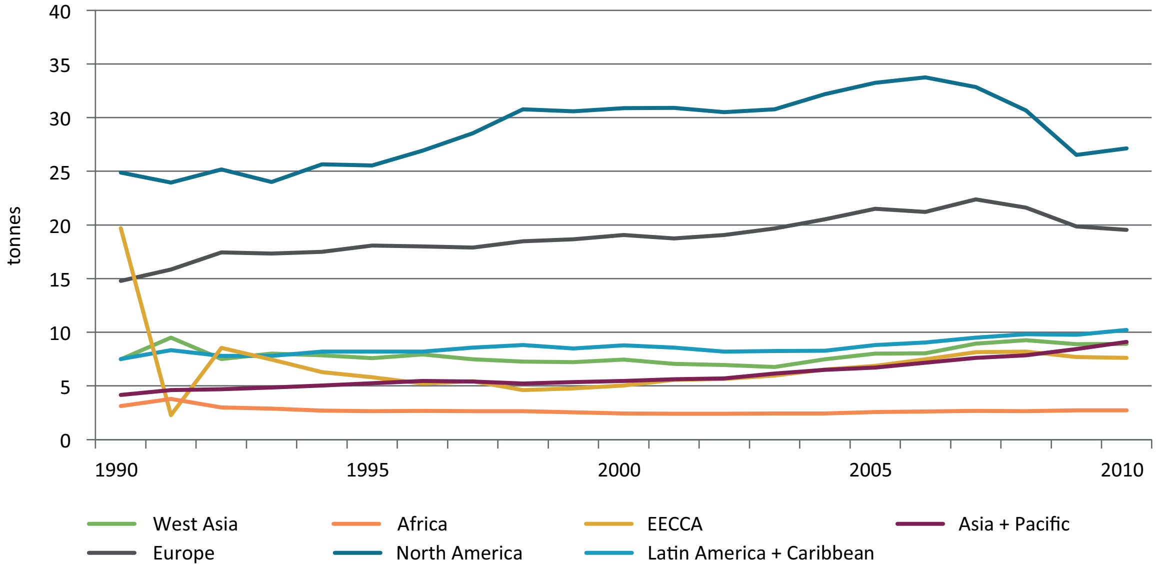


Figure 33. Per capita material footprint of consumption (MF) by seven world regions, 1990–2010, tonnes

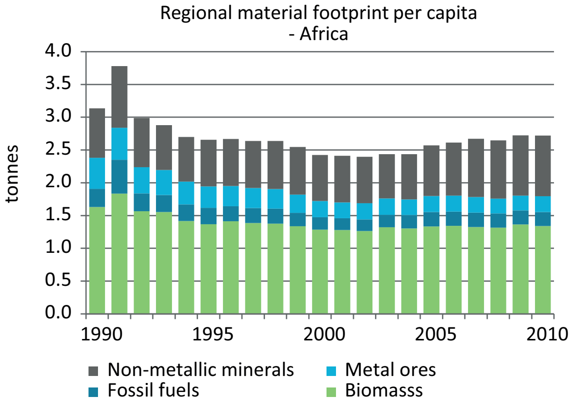
capita tended to decrease further on MF per capita, especially Africa. The most pronounced change was for the EECCA region, with much reduced MF per capita, while for both Latin America and the Asia-Pacific the main change was a reduction in the rate at which MF per capita grew compared to DMC.

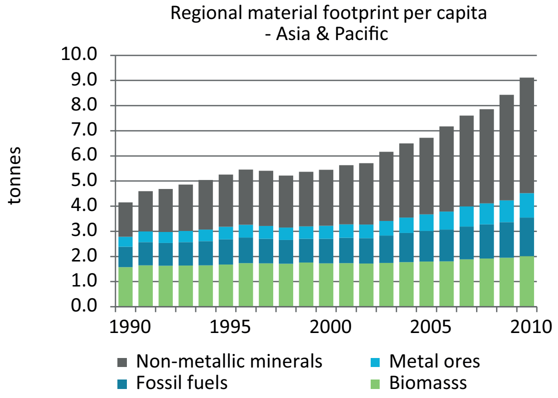
Comparing the more detailed breakdown of MF per capita by material groups in Figure 34 to Figure 30, in most cases there appears to be a scaling up or down of individual materials categories roughly proportional to a region's MF: DMC ratio. One clear exception to this is for the EECCA region, where the decrease in the three non-biomass categories, especially fossil fuels, was much larger than for biomass. Another disproportionate decrease is seen in West Asia's fossil fuels. As fossil fuels typically undergo relatively little direct concentration prior to trade, the decrease in fossil fuels in these two cases is perhaps accounted for by the large-scale transformation of fossil fuels to some other bulk commodity for export, e.g. inputs of natural gas into nitrogenous fertilizer production.

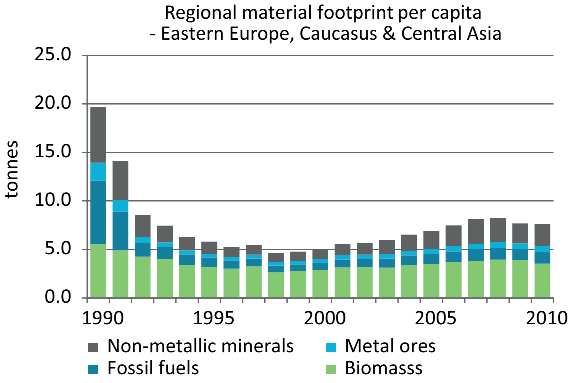
Figure 34. Per capita material footprint of consumption (MF) by seven world regions, 1990–2010, tonnes

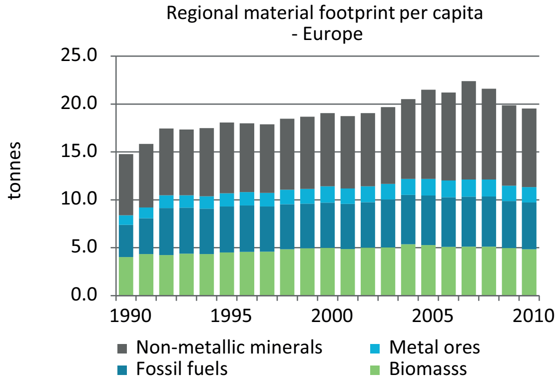
3.5 Material intensity of the economy

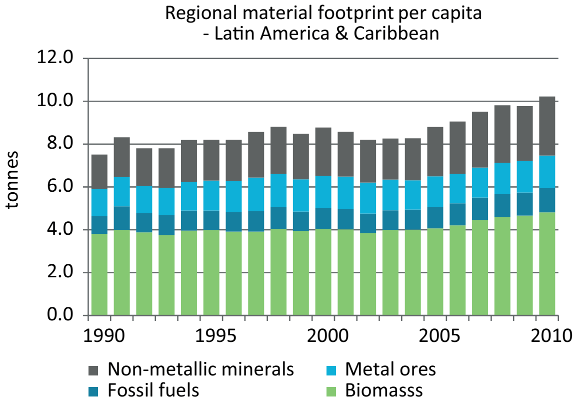
In this section the efficiency with which the seven regions convert their material inputs to GDP is examined. The lower the material intensity (MI) of a region, the more efficient it is at creating wealth from each unit of material input. Following the preceding discussions

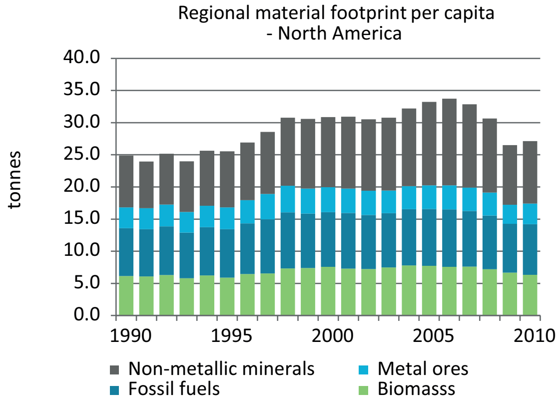

Regional material footprint per capita - Africa

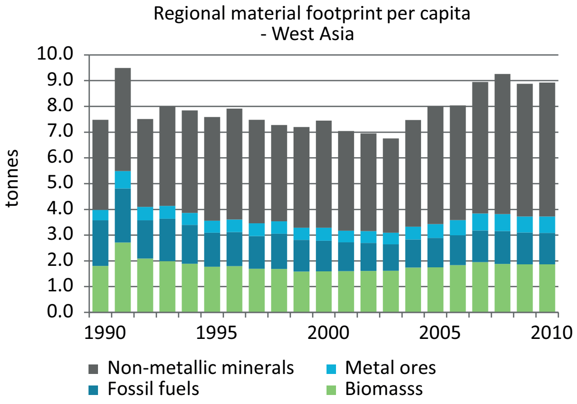

Regional material footprint per capita - Asia & Pacific


Regional material footprint per capita - Eastern Europe, Caucasus & Central Asia


Regional material footprint per capita - Europe


Regional material footprint per capita - Latin America & Caribbean


Regional material footprint per capita - North America


Regional material footprint per capita - West Asia

on the major differences between direct material consumption, determined on a territorial basis, and final consumption which takes into account upstream inputs, two different metrics of material intensity are used. The conventional measure of MI is simply DMC/GDP, expressed in kg per $. The second metric used below is adjusted material intensity (AMI) which is MF/GDP, also expressed in kg per $.

In Figure 35, MI and AMI are plotted for each region, together with global MI as a reference. One feature which emerges clearly from an overview is that more affluent regions (higher GDP per capita) tend to have low MI (i.e. create more wealth for each unit input of primary materials). Thus we see that Europe and North America, which had GDP per capita in 2010 of $25872 and $42830 respectively, have MI levels around one half or less of global average MI, while Africa, the Asia-Pacific and Latin America, with GDP per capita in 2010 of $1284, $3513 and $5684 respectively, had MIs around 1.5 to 2.5 times the global average.

It is important to note that the bias towards lower MI / higher resource efficiency for the richer countries is an expected and largely inevitable outcome of their economic structure. In many cases, more affluent nations have large elaborately transformed manufactures (ETM) sectors, which typically add great value to each unit of material used. This is a clear case of using materials more efficiently. However, some affluent countries have industrial sectors dominated by low value added primary and processed primary production. There are also a number of poor countries which have much higher proportions of their industrial sector in ETMs than some affluent countries, which nevertheless still exhibit higher resource efficiency than the poorer countries. A second dynamic which can help explain this latter situation is that affluent countries tend to have relatively large service sectors, which also add more value per unit of material consumed than primary industries. There is however one additional factor which tends to ensure that affluent countries have relatively low MI. The simple property of being affluent implies a high wage cost structure, which in turn means that the value added for an identical service will be much higher in a rich country than a poor country. This inevitably boosts the apparent material efficiency of a wealthy country relative to poorer countries, especially when the GDP measure used is exchange-rate based, as here.

There is a more subtle pattern in Figure 35 which again relates to the relative affluence of regions. The two most affluent regions both show relative decoupling (of materials use from economic growth) on the MI metric, but the degree of decoupling decreases (or stops entirely in the case of Europe) when we look instead at AMI. When we look at the less affluent countries, we usually see the reverse, i.e. the degree of relative decoupling is usually greater using AMI. This is a result of the AMI indicator reallocating the materials consumed in these

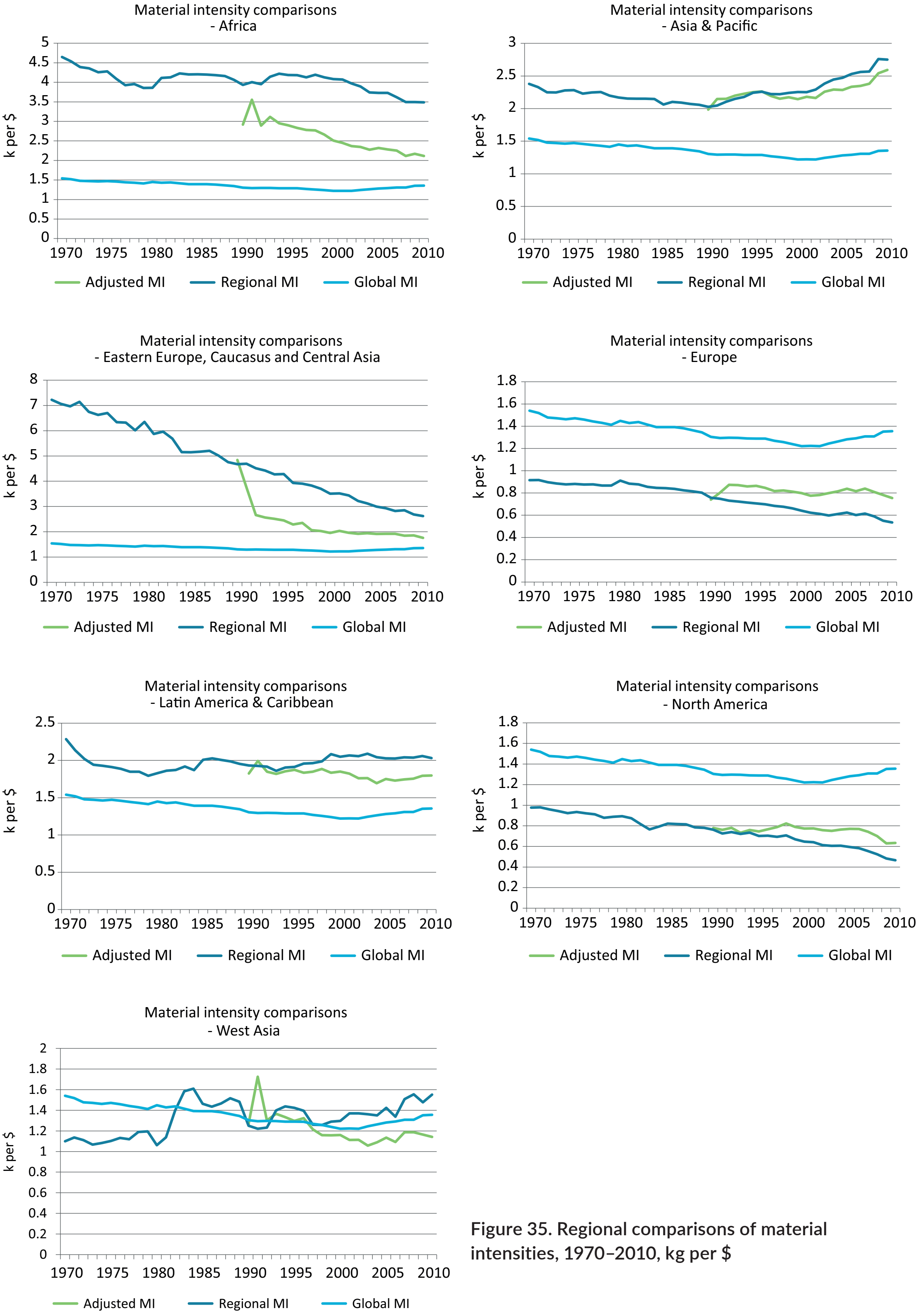


Figure 35. Regional comparisons of material intensities, 1970–2010, kg per $

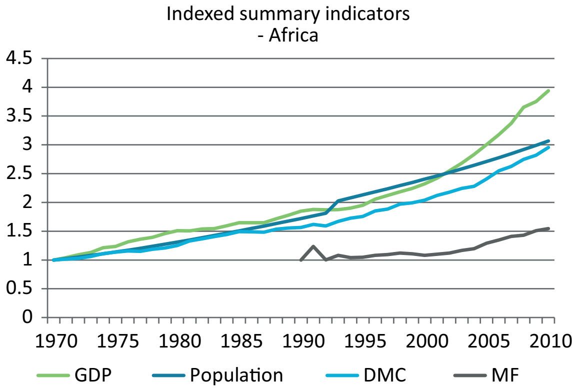
regions as an intermediate step to the regions where final consumption takes place. This is of potential importance in explaining the apparent Environmental Kuznets Curves postulated for more advanced economies. A mechanism for the improved environmental efficiency and outcomes often observed as nations become more affluent, is that a wealthy country is more inclined and able to impose higher environmental standards, ensuring more efficient and cleaner production. An alternative explanation, consistent with the divergence between MI and AMI, is that improved environmental standards achieve much of their effect by encouraging offshoring of the more material- and energy-intensive, as well as polluting, industries.

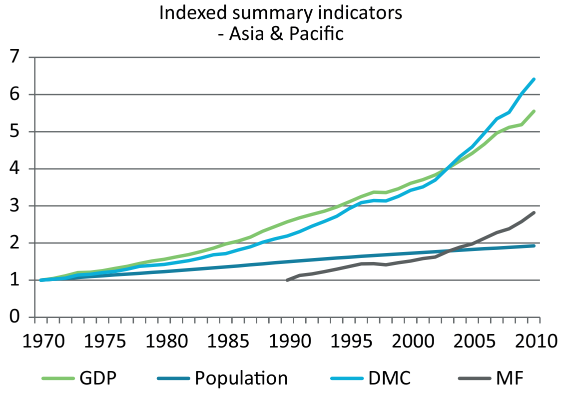
3.6 Regional trends

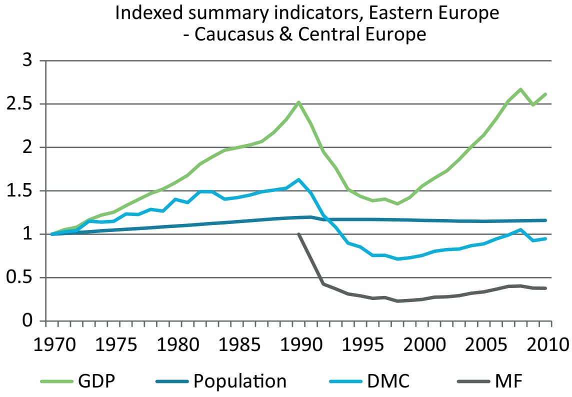
Figure 36 contains a selection of summary indicators for each of the seven regions. GDP, population, and DMC are all indexed to 1970 = 1.0, while MF is indexed so that 1990 = 1.0.

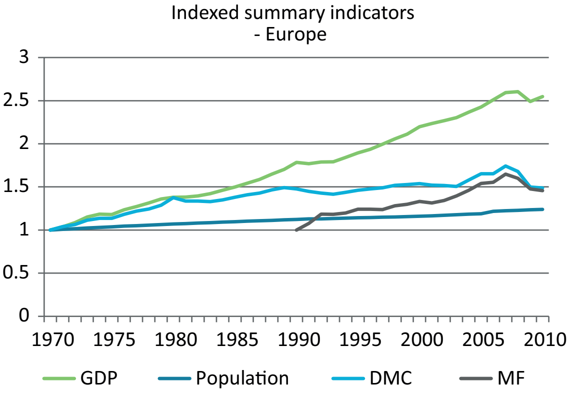
Material use and human development

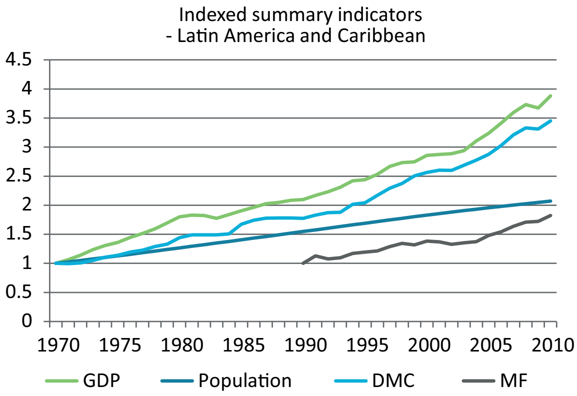
The improvements in human development experienced by many parts of the world over the past four decades have been underpinned by large and growing extraction of primary materials. While the relationship between the use of natural resources and human development outcomes has been studied for energy use and carbon emissions, e.g. Steinberger and Roberts (2010), there has

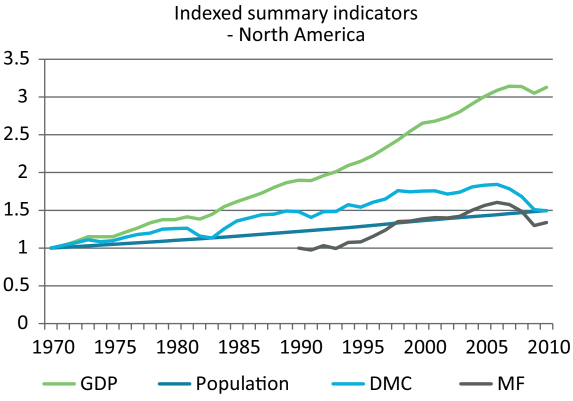












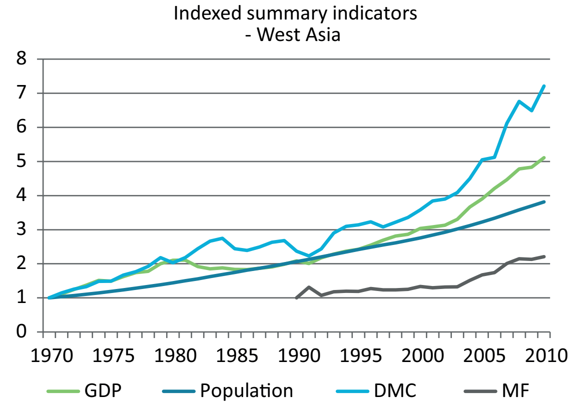
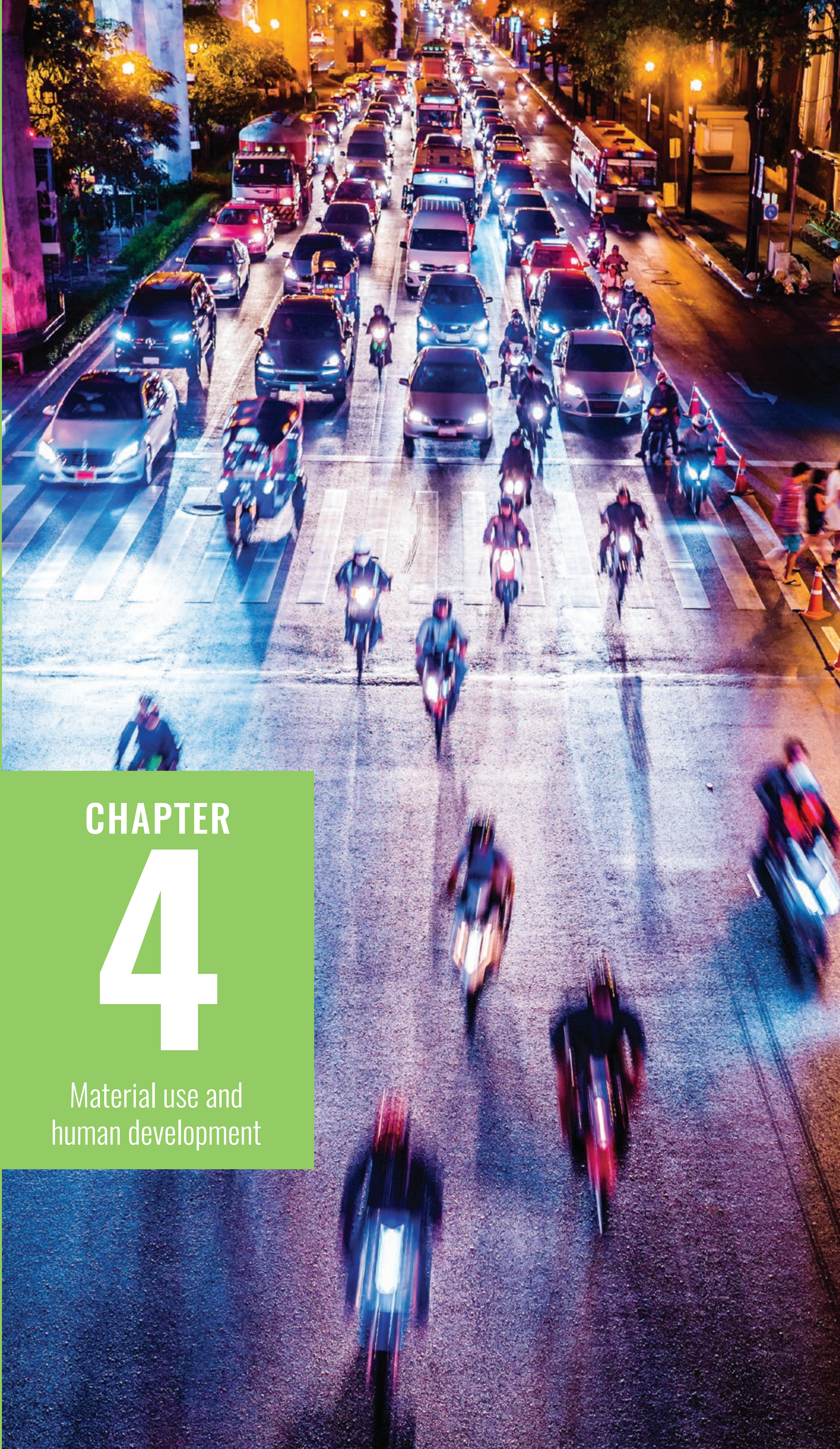


Figure 36 Regional trends in GDP, population, DMC, and MF, 1970–2010, index 1970 = 1



CHAPTER

4

Material use and human development

been less work done on its relationship to materials. To explore the relationship between human development and the consumption of primary materials, we use the national level human development index (HDI) as the metric for development, and relate that to both territorial and footprint based indicators of material flows and consumption.

The HDI metric was developed to provide a more policy relevant measure of human development which took a broader view of the factors which contribute to development than traditional measures as GDP per capita. The HDI takes three key dimensions of human development into account: life expectancy, education and per capita income. HDI data are available from the United Nations Development Programme (UNDP) for most countries in the world. Four broad bands of national HDI have been defined: very high, high, medium and low.

Figure 37 shows that the very high HDI (VHDI) countries have the highest levels of DE in per capita terms, at around 18 tonnes per capita for most of the decade leading up to 2008. Economic stagnation after the GFC, and the slowing of demand for primary resources that accompanied it, meant that material extraction dropped to 16 tonnes per capita in 2009–10. It is likely that DE for the VHDI group will resume growth if and when the economies of the United States and Europe return to higher economic growth levels. In contrast to the VHDI group, per capita material extraction was largely unaffected by the GFC in high HDI (HHDI) countries (a group that includes the many Asian and Latin American economies currently undergoing industrialization), and continued on a very strong growth trajectory. The medium HDI (MHDI) group showed continuing but more muted growth than the HHDI group, while the low HDI (LHDI) group

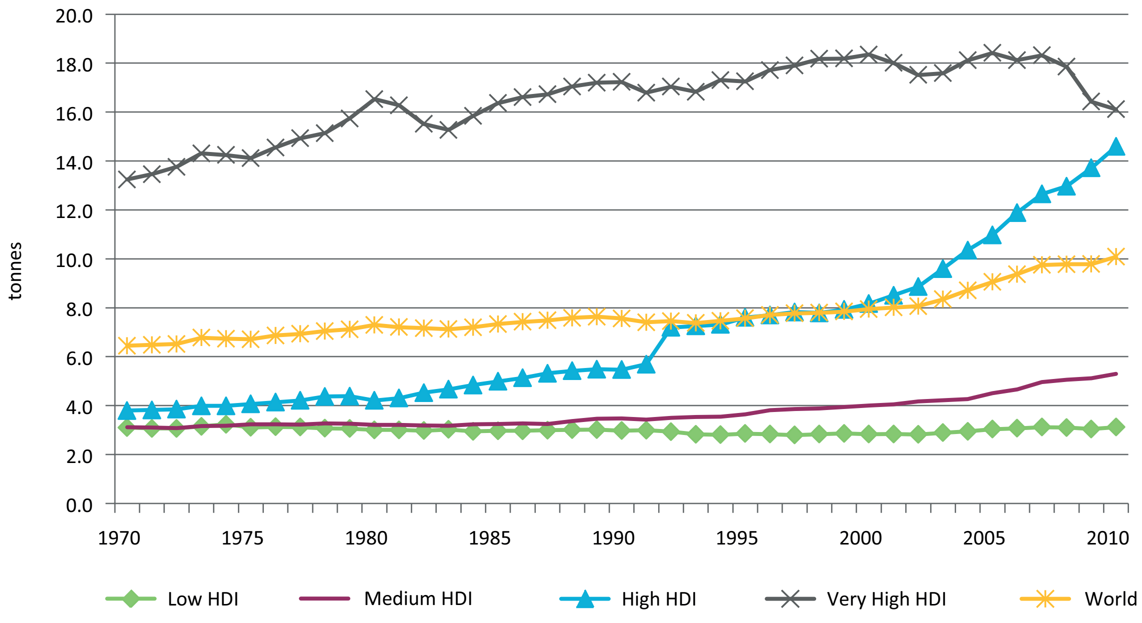


Figure 37. Per capita domestic extraction of materials (DE) by development status, 1970–2010

showed little growth in per capita extraction, with levels remaining capita extraction is much lower at around one fifth to one quarter the 2010 levels of VHDI and HHDI countries. The contrast between the stagnation seen in DE per capita for the LHDI group compared to the MHDI and HHDI groups is likely attributable to a number of factors. The most obvious one is that the LHDI group has by far the most rapid population growth. Population growth reduces any per capita measure in inverse proportion. A second factor is likely to be risk aversion on the part of foreign investors. Major modern extractive industry projects require massive investment and long payback periods. The stable socioeconomic and political conditions that help secure such investments are more likely available in countries that have achieved a higher HDI.

In Figure 38 we find that for the VHDI group, the high per capita supply of materials provided from DE is further augmented by high net imports of materials from other countries. Their net imports of materials reached levels of around 1.3 tonnes per capita be prior to the GFC, falling to less than one tonne per capita in its aftermath. All of the other HDI groups were net exporters of materials on a PTB basis. Interestingly, the highest net exporters were the HHDI group, rather than the lower HDI groups. This is consistent with the idea that major investments for extractive export infrastructure are attracted to the more stable and secure environments offered by nations with higher HDI levels.

In Figure 39 we see that when trade flows are corrected for the upstream requirements of

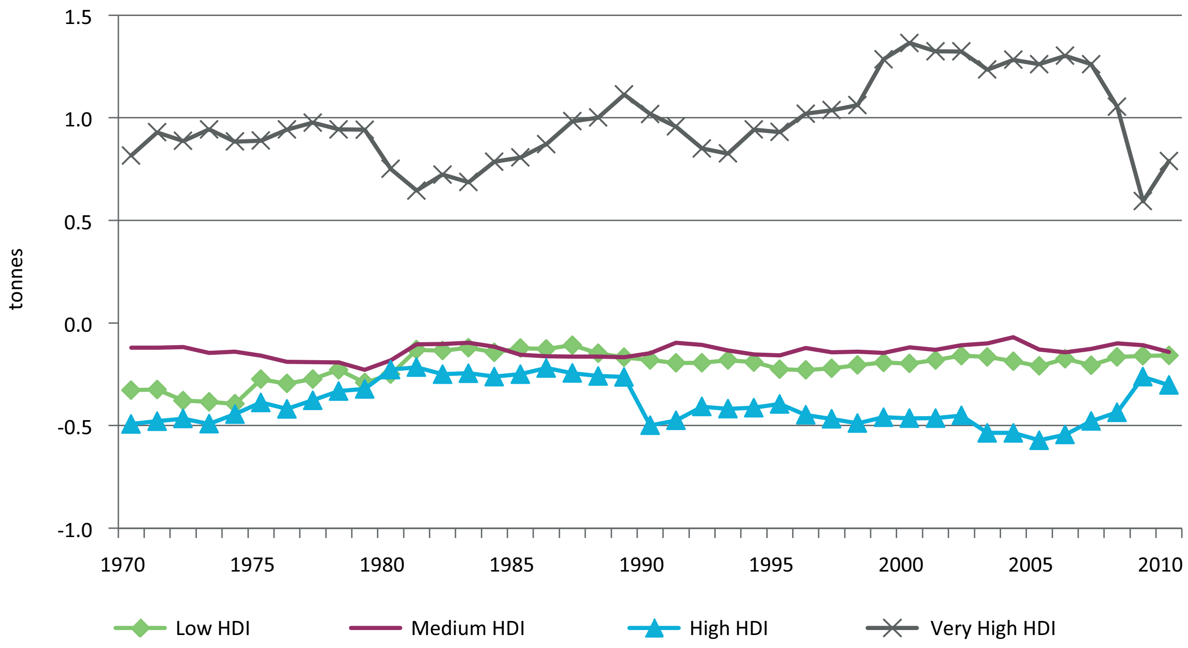


Figure 38. Per capita physical trade balance (PTB) by development status, 1970–2010

that trade (using the RTB metric), the VHDI group shows a very large increase in its raw material inputs from trade, with pre-GFC levels above eight tonnes per capita, falling to around six tonnes immediately after, and already rebounding somewhat by 2010.

In Figure 40, DMC shows a very similar trend to DE, indicating that in raw in tonnage terms, the lion's share of materials that are input directly to most economies are extracted locally. This ignores the effects of concentration in trade, discussed in Chapter 3. The curve for DMC per capita for the VHDI group moved marginally higher than DE overall, while the HHDI group moved marginally lower, but even after this adjustment it is clear that the very rapid growth since the turn of the century for the HHDI group led to per capita DMC levels approaching those of the VHDI group. Indeed, if both groups maintained their trajectories as of 2010, the HHDI group might have surpassed the VHDI group in DMC per capita. As for DE, DMC for the MHDI group grew strongly but had still only reached levels a third of the VHDI counties by 2010. The per capita DMC of the low HDI group is strikingly low (at only 3 t/cap/y), a level which changed little over the four decades.

While the HHDI group has reached levels of DMC per capita roughly comparable to those of the VHDI group, this has not as yet translated into a similar standard of living. One reason for this is the familiar exclusion of upstream embodiment of materials in the DMC measure. The MF perspective which remedies this will be discussed below, with reference to Figure 41. A second factor, not discussed previously,

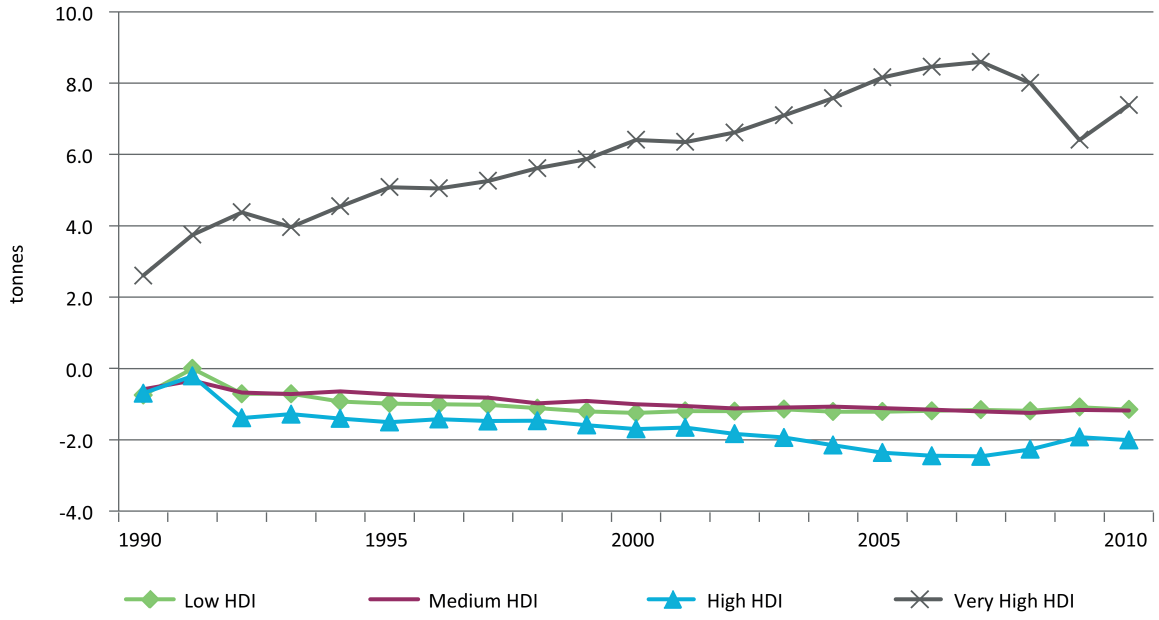


Figure 39. Per capita raw material trade balance (RTB) by development status, 1990–2010

is the degree to which current living standards depend not just on current inputs of materials and energy, but also on accumulated and embodied stocks of those inputs (Fishman et al. 2014). The stocks of housing, civic infrastructure such as hospitals and schools, power and water utilities, manufacturing plant, and transport infrastructure are vital in determining the standards of living experienced by residents, and for building the human capital of a society. All of these stocks are built up over many decades, and then typically have long service lives. A rough indicator of the current gap between the VHDI group and other groups on this component of living standards might be gleaned by looking at the total area under their respective curves, rather than looking at the relative levels at specific points in time. Integrating each curve in this way suggests that even if the HHDI group pass the VHDI group in DMC per capita terms, it would be some time before living standards became equal.

In Figure 41 we see that using the MF per capita greatly increases the gap between the VHDI countries and other groups, compared to DMC per capita. The greatest relative change in position is between the VHDI and HHDI groups, especially for the most recent decade. Rather than approaching parity with VHDI levels by 2010, HHDI MF per capita remained at around one half VHDI levels. This can in large part be explained by the huge investments the HHDI group (dominated by China) have made in building up manufacturing and other infrastructure which is geared towards creating manufactured goods for export. In effect, the development model followed by the dominant HHDI countries is one of embedding primary materials in manufactured goods for sale. The MF indicator, it must be remembered, will

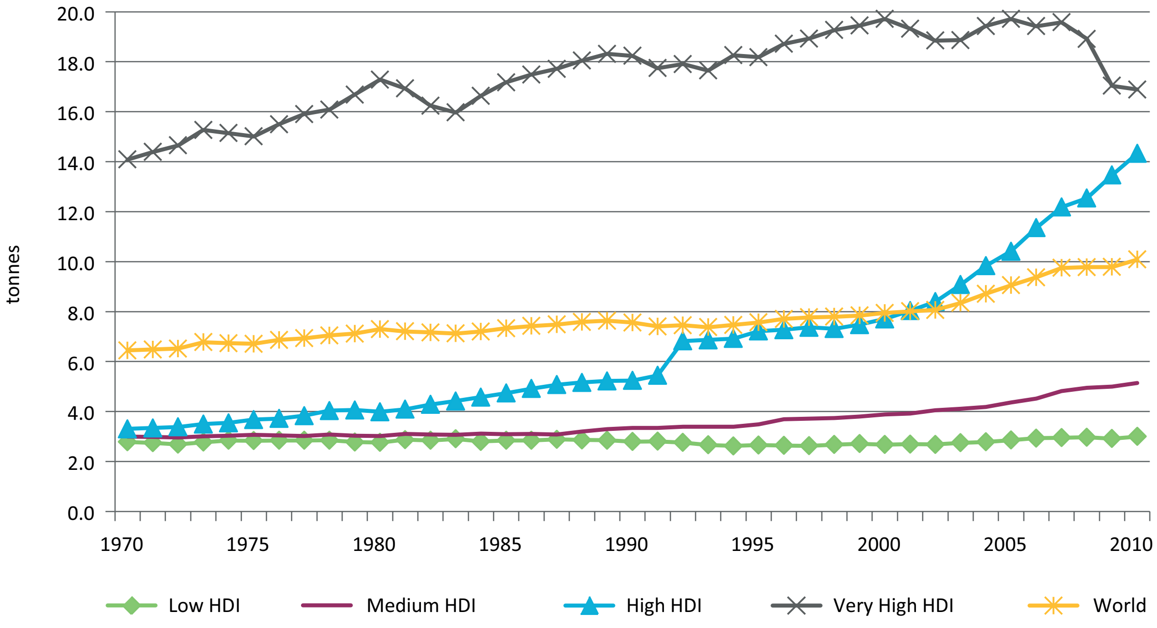


Figure 40. Per capita domestic material consumption (DMC) by development status, 1970–2010

attribute not only the materials used directly in the manufacturing process, but also a share of those invested in the manufacturing plant, transport infrastructure and even residential buildings. As seen earlier in the report, the largest single DMC item in recent years has been of construction minerals, and much of that was attributable to China. The MF indicator will reallocate a large portion of those construction materials to the export destinations of Chinese manufactured goods. As China has become such a dominant source of supply of many manufactured goods, to both rich and poor countries alike, some of this reassignment will be to MHDI and LHDI countries. This perhaps explains the very limited change in MF per capita profiles for MHDI and LHDI countries from those already described above for DMC per capita.

A reverse pattern can be observed for the material intensity of the economy (Figure 42). The LHDI and MHDI countries require 6 to 10 times more materials to produce a unit of GDP than the group of VHDI countries. The reasons for this, including their industry mix, relative shares of service to material intensive activities, and low wage structures, have been discussed in more detail previously in Chapter 3. Material intensity improved most in absolute terms in the MHDI countries, decreasing by 2.4 kg per % between 1970 and 2010. The LHDI group actually experienced a small increase in MI over much of the first three decades, followed by a rapid decrease from the mid-1990s. The accelerated decrease in MI for the LHDI group can in large part be explained by increasing commodity prices. The rapidly growing HHDI countries, in contrast, do not

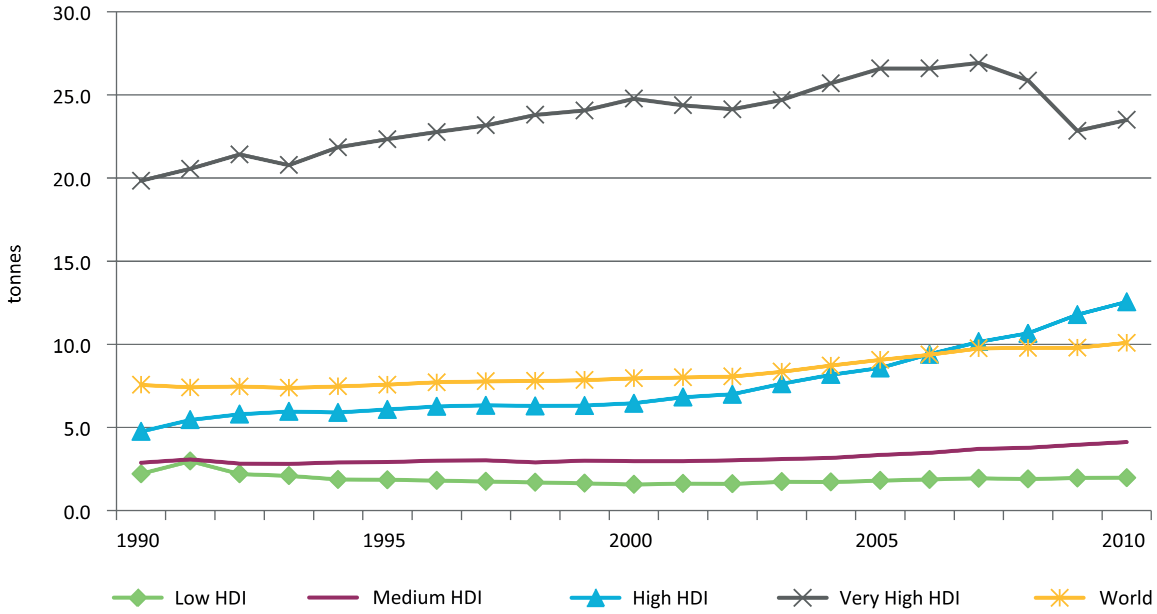


Figure 41. Per capita material footprint (MF) by development status, 1990–2010, line graph

show improvements in material intensity. For this group, material use has grown at or above the rate of GDP growth since the turn of the century. For the VHDI group, the decrease in MI has been small in absolute terms (0.4 kg per $), but came off a very low base. The relative rate at which material efficiency improved for the VHDI countries was in fact the highest of any group, with MI decreasing by 43% between 1970 and 2010.

Comparing Figure 43 to Figure 42, we see how the material efficiency of the different HDI groups changes when we use a footprinting basis to attribute materials consumption. The changes are consistent with what we would expect from previous discussion of the differences between the DMC and MF metrics. The AMI for the VHDI group is higher than MI, and does not improve much as MF continues to include inputs to local consumption that have been off-shored. The AMI of all other HHDI groups is lower than for MI.

In Figure 44 we see that for the LHDI group, population, GDP and DMC grew in concert until recently, and only started to decouple in the past decade when GDP growth broke trend and accelerated quite rapidly, while growth in population and DMC remained relatively stable. This led to increased per capita incomes and material standards of living for the first time in

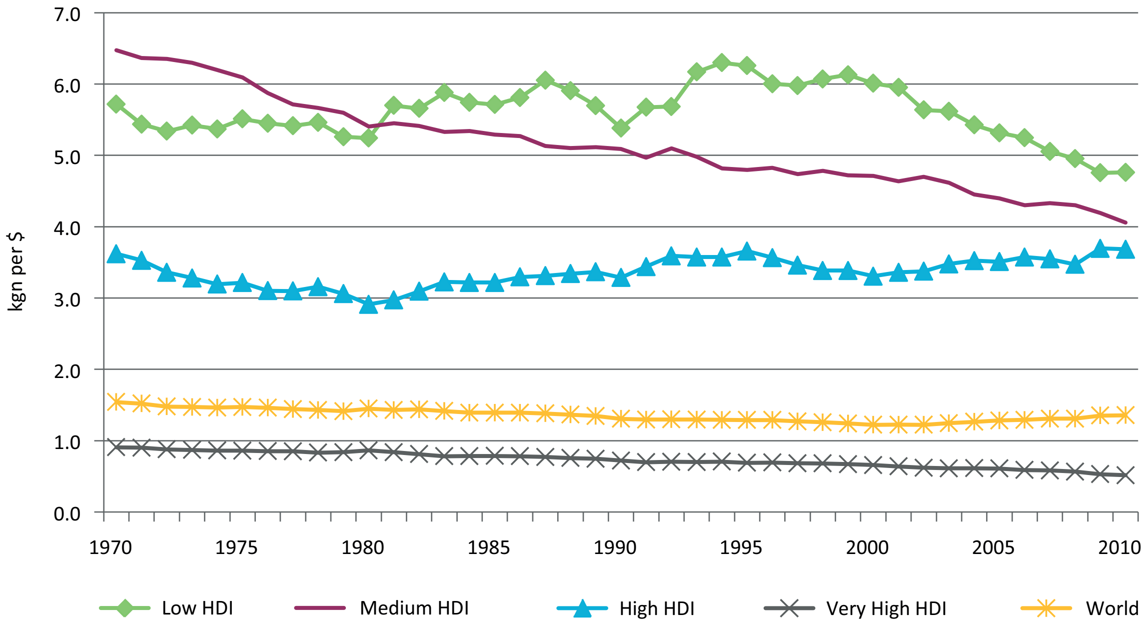


Figure 42. Material intensity (DMC per unit of GDP) by development status and global material intensity, 1970–2010

more than four decades. The MF trend from 1990 reflects the last decade of this period of stagnation in total final consumption (and a decrease in per capita terms), then from 2000 on the increased ability to consume in the LHDI countries precipitated by rising affluence. Over this final decade total MF increased by 60%.

In Figure 45 we see DMC for the MHDI countries quadrupling over the four decade period, marginally higher than the tripling we saw previously for the LHDI group. A much more significant difference is that the MHDI group experienced both significantly higher rate of economic growth (with GDP increasing more than sixfold over four decades) and lower rates of population growth (doubling since 1970) compared to the LHDI group of countries. This translates into a much faster increase in affluence. The effects of this from 1990 to 2010 are reflected in the growth in MF, which shows consistent growth from the early 1990s, with total MF doubling by the end of the period. Taken together with the lower population growth rate, this indicates that overall, this group has done significantly better in terms of development than the LHDI group.

Figure 46 shows that DMC grew almost fivefold between 1970 and 2010, much faster than for the LHDI group and somewhat faster than the MHDI group. The group of HHDI countries has similar levels of GDP growth to the MHDI group, and significantly lower levels of population growth, which indicates even faster growth in affluence than seen for that group. The attendant increased power to consume is reflected in the faster growth in MF than seen for either of the previous groups, which increased by roughly 220%

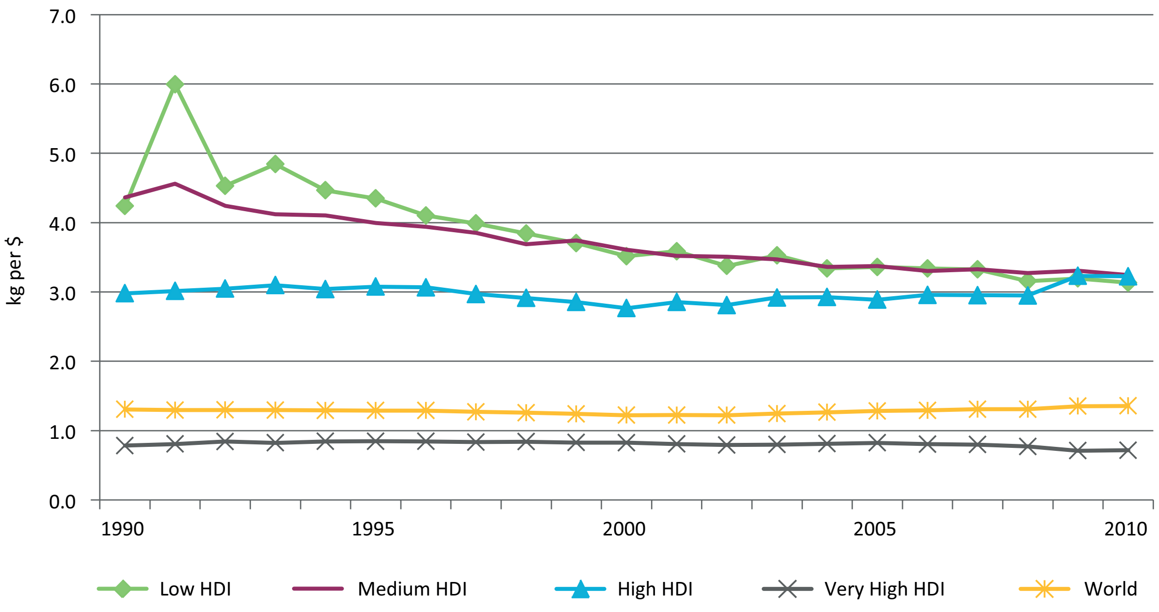


Figure 43. Adjusted material intensity (MF per unit of GDP) by development status and global material intensity, 1990–2010

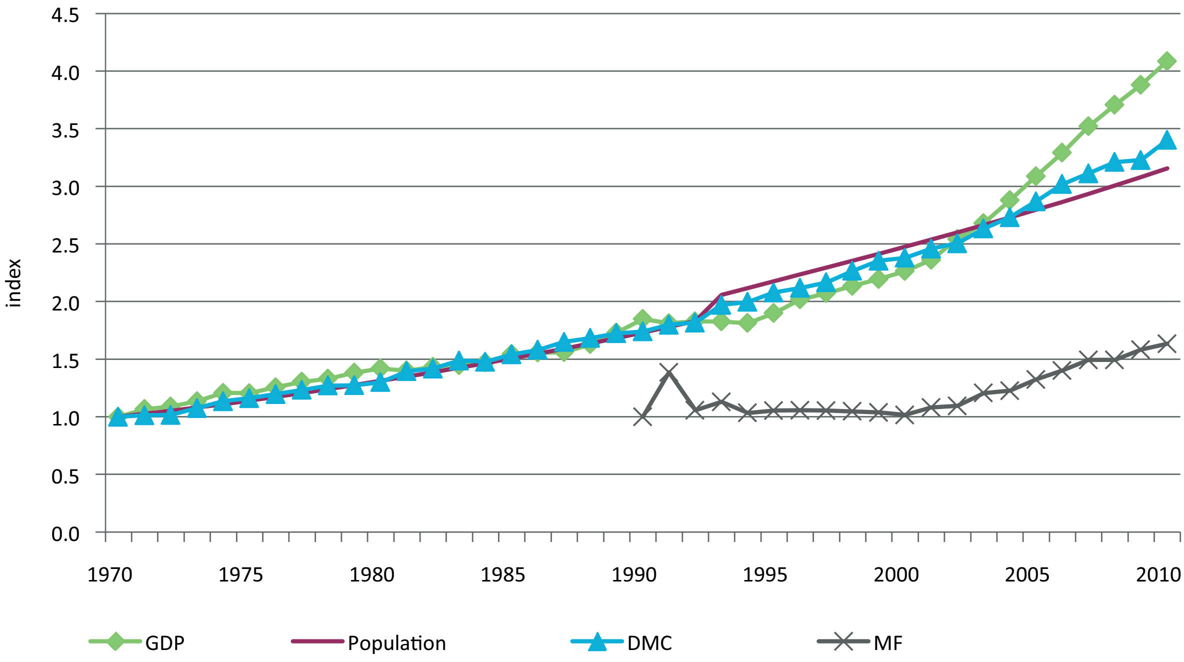


Figure 44. GDP, population, DMC, and MF in low HDI countries, 1970–2010, index 1970 = 1

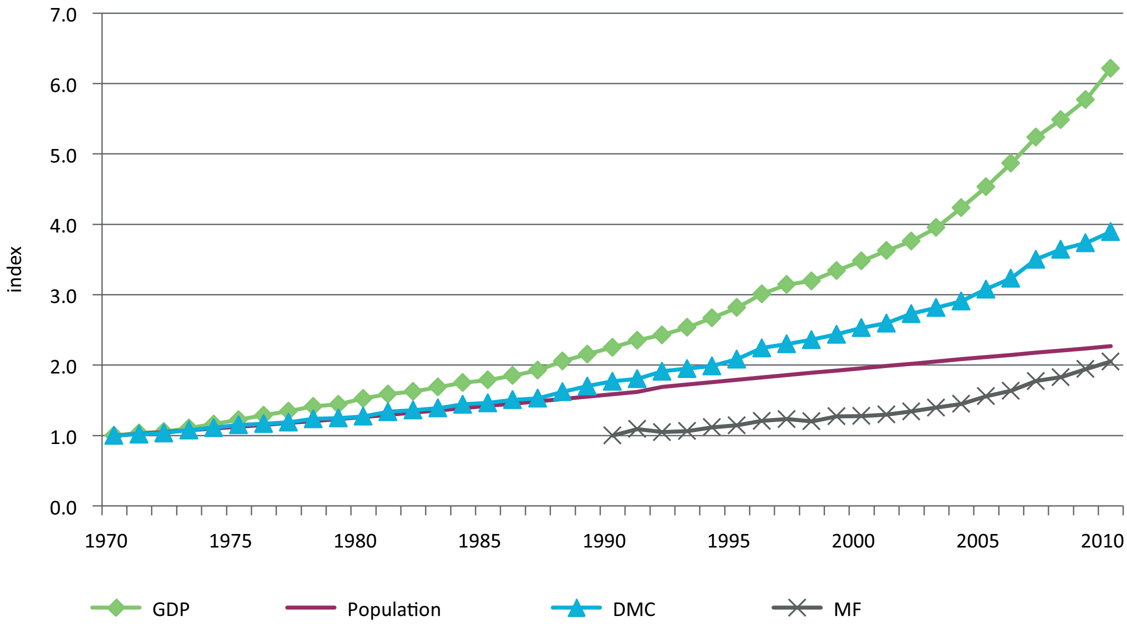


Figure 45. GDP, population, DMC, and MF in medium HDI countries, 1970–2010, index 1970 = 1

between 1990 and 2010. Interestingly, this greater performance over the last two decades came despite an initial major decrease in MF, with 1990 levels of MF only regained by the mid-1990s. This initial dip reflects the economic dislocations suffered by the large ex-Soviet republics included in this group.

Starting from a far higher base than the other HDI groupings, the VHDI countries experienced the lowest growth in DMC and GDP over the period 1970 to 2010. This group also had the lowest growth in population, which in conjunction with the GDP growth rate left it with a relative increase in affluence much higher than the LHDI group, much lower than the HHDI group, and broadly comparable to the MHDI group. While the degree of relative decoupling of GDP and DMC was largest for this group, it was still not enough to lead to a reduction in total material use as measured by either DMC or MF. The strong drop in GDP, DMC and MF from 2008 clearly observable for this group, and largely absent for the others, demonstrates the degree to which the effects of the GFC were concentrated in the VHDI countries. While GDP growth had recovered by 2009, DMC and MF levels remained well below 2008 levels.

The discussion about the relationship of material use and human development has shown, not surprisingly, that the most developed nations have the highest level of per capita resources available to support their long, healthy, and affluent lives. In this section we focus on the question of whether the per capita materials use required to attain high levels of human development has changed over time. This line of analysis was encouraged by previous research, notably (Steinberger and Roberts 2010, Lamb et al. 2014), which found that the relationship between energy use and

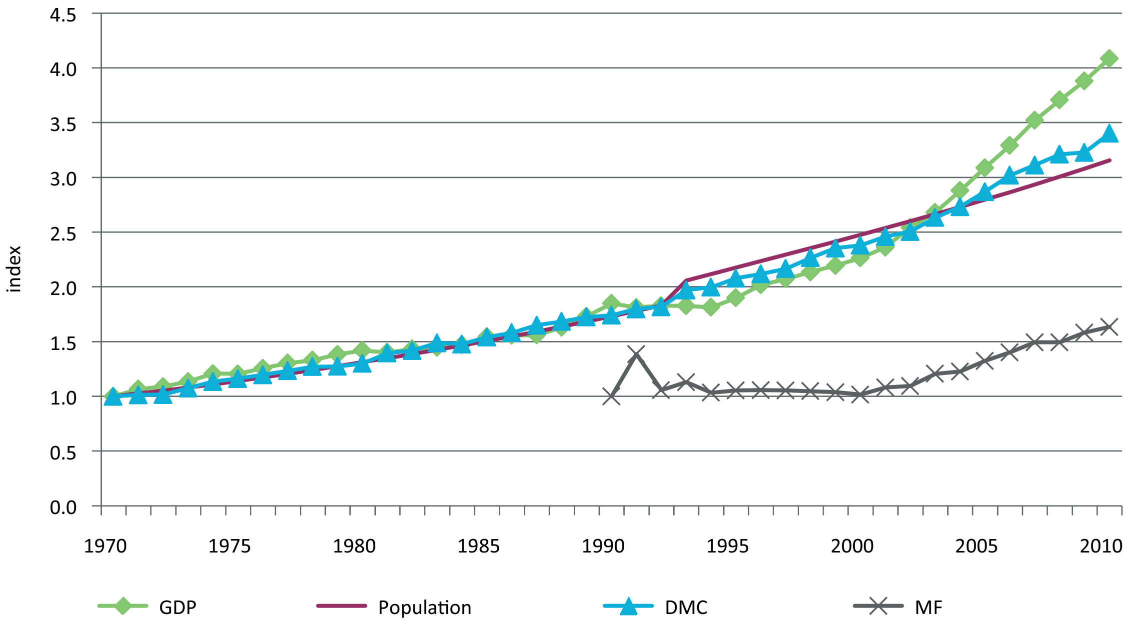


Figure 46. GDP, population, DMC, and MF in high HDI countries, 1970–2010, index 1970 = 1

greenhouse gas emissions is non-linear. Instead, this relationship can be described by logarithmic regression curves, indicating that a plateau exists beyond which additional energy use is no longer associated with significant improvements in human development. The development of these curves over time additionally shows that the amount of energy and emissions required for a high level of human development have continuously decreased. We replicate the method used by Steinberger and Roberts (2010), using per capita domestic material consumption and per capita material footprint with HDI in a regression analysis.

UNEP material flow data is available for 233 countries between 1970 and 2010 for domestic material consumption (DMC), and for 186 countries between 1990 and 2010 for the material footprint (MF). Not all of this data can be used in a regression analysis because of data gaps, (especially but not exclusively in the case of small island states). Population data for all years was sourced from the United Nations population database.

The human development index (HDI) is reported by the United Nations Development Programme (UNDP) for the following years overlapping with material flow data availability: 1980 (124 countries), 1990 (141 countries), 2000 (158 countries), 2005 (174 countries), 2008 (175 countries), and 2010 (187 countries). In terms of the HDI components, data on life expectancy at birth (years), gross national income (GNI) per capita (PPP) in constant 2011 US$, and data on mean years of schooling are reported by the UNDP in the Human Development Reports (also see table below for coverage coinciding with material flow data).

Together, this renders the following sample sizes (n corresponds to number of countries

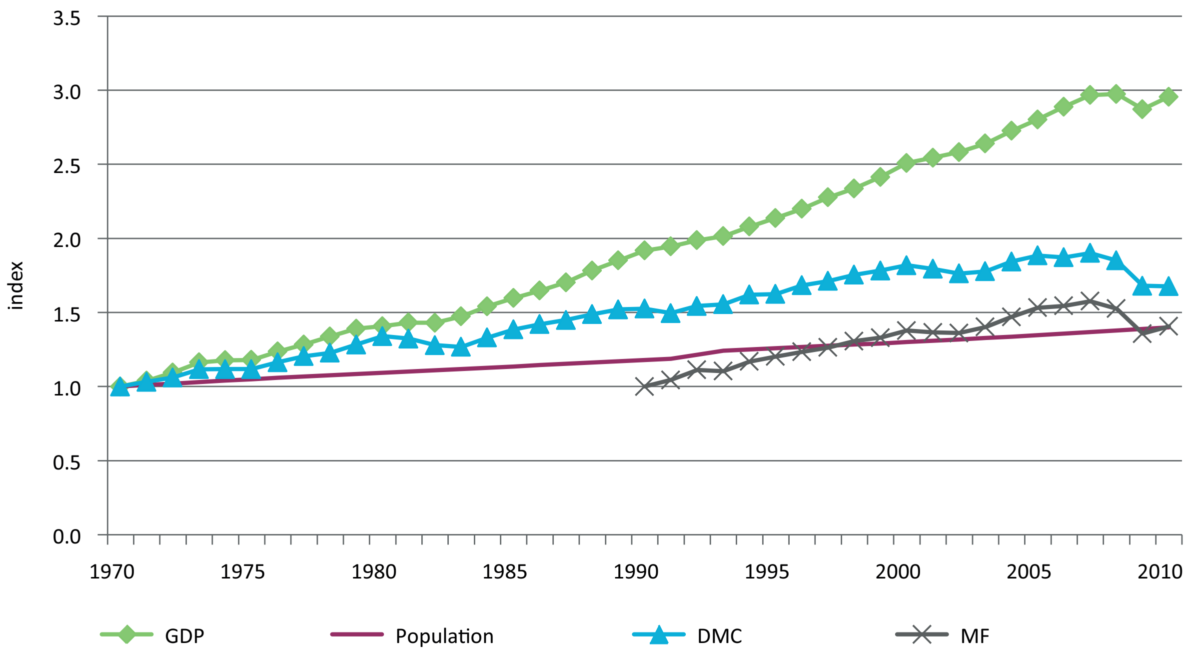


Figure 47. GDP, population, DMC, and MF in very high HDI countries, 1970–2010, index 1970 = 1

for which both material flow and HDI data are available) for the analysis (see Table 5).

To avoid a bias of the sample size on the regression results, the analysis was conducted for the number of countries for which data was available for all points in time (1980–2010 for DMC and 1990–2010 for MF).

For both DMC and MF per capita values were used in the regression. Since the per capita consumption of larger countries (population-wise) has a stronger impact on global material consumption, the data points were weighted by the population size to which they correspond. The per capita DMC or MF of countries with a large population (e.g., China and India) was thereby more influential in determining the relationship to the HDI and its components than the corresponding indicator for countries with small populations (e.g., Malta and Tonga). The goodness-of-fit (r^2) is reported for the population-weighted least squares.

The regression relationships follow the following form for both DMC and MF:

$y = a*\ln(x) + b$

where y is HDI and x is DMC or MF. The goodness-of-fit in the results (see Table 5) applies to the logarithmic relationship.

An overview of the regression results for DMC and MF relationships to HDI and its components is provided in Table 6. The columns labelled “threshold” provide information on the material flow level (DMC or MF) which was required in order to obtain a specific value for each indicator in each respective year. For HDI, the threshold for “very high human development” (HDI > 0.8) was examined, for GNI medium income in 2011 (10 500 US$, PPP) was used. The threshold for life expectancy chosen was 70 years and for education, 7 years of schooling were used. These values can easily be adapted for further analysis.

It is worth noting that the relationship between HDI and the material flow indicators changed most noticeably for GNI when the data was weighted by population. This is due to the fact that countries with very high GNI (Brunei Darussalam, United Arab Emirates, Kuwait) very strongly impact the trend line without population weighting and have less of an impact when the data is weighted by population. This means that no countries actually reach the 10,500 US$ income with the indicated low material use level. For further analysis, it might be more useful to analyse income weighted by share in global income rather than population.

Table 6. Regression results for DMC and MF compared to HDI and its components

The material threshold required for a very high HDI has been consistently declining since 1980 (or 1990 for the MF). While (mathematically) 35 t/cap of DMC (or 33 t/cap of MF) were required in 1990 in order to achieve a very high HDI, this amount decreased to 21 t/cap of DMC and 14 t/cap of MF by 2010 (also see figures below for visualization).

Table 5. Sample size for regression analysis of the relationship between material use and HDI

	1980	1990	2000	2005	2008	2010
DMC and HDI	n = 120	n = 121	n = 151	n = 166	n = 168	n = 177
MF and HDI	-	n = 121	n = 137	n = 152	n = 163	n = 174

LEGEND: Regression results for DMC (top) and MF (bottom) compared to HDI, the sketched log-relationship corresponds to the goodness-of-fit indicated in Table 6 above for population-weighted least squares. Note that the maximum MF footprint is smaller than the maximum value for DMC and the x-axes are not to the same scale.

This analysis confirms the findings of Steinberger and Roberts (2010) and Lamb et al. (2014) that the per capita amount of natural resources required to underpin a high human development level are in fact decreasing over time. If this decoupling between human development and material use improves faster than population grows, it should relieve global demand for primary materials while simultaneously permitting ongoing increases in living standards.

This overall result is, however, largely driven by the life expectancy and education components of the HDI. There is no such pattern for income. The greatest improvements have been

Domestic material consumption

	HDI		GNI (2011 US$, PPP)		Life expectancy (years)		Schooling (years)	
	120 countries		145 countries		148 countries		123 countries	
	R^2	Threshold	R^2	Threshold	R^2	Threshold	R^2	Threshold
		0.80		10 500		70		7
1980	0.85	45.13	0.83	5.32	0.83	22.86	0.84	21.82
1990	0.83	35.45	0.82	5.66	0.82	14.91	0.83	13.01
2000	0.82	27.78	0.81	5.28	0.81	12.49	0.82	8.49
2005	0.82	24.52	0.81	5.24	0.81	11.32	0.82	6.98
2008	0.82	22.83	0.81	5.08	0.81	10.15	0.82	6.52
2010	0.82	21.18	0.82	4.86	0.82	8.74	0.82	5.90

Material footprint

	HDI		GNI (2011 US$, PPP)		Life expectancy (years)		Schooling (years)	
	120 countries		145 countries		147 countries		123 countries	
	R^2	Threshold	R^2	Threshold	R^2	Threshold	R^2	Threshold
		0.80		10 500		70		7
1990	0.82	32.69	0.80	3.63	0.79	7.56	0.81	10.13
2000	0.82	18.80	0.80	2.99	0.81	8.22	0.82	5.30
2005	0.84	15.48	0.82	2.87	0.82	6.60	0.84	4.36
2008	0.84	14.30	0.82	2.72	0.82	5.61	0.83	3.89
2010	0.82	13.77	0.80	2.63	0.80	4.98	0.82	3.48

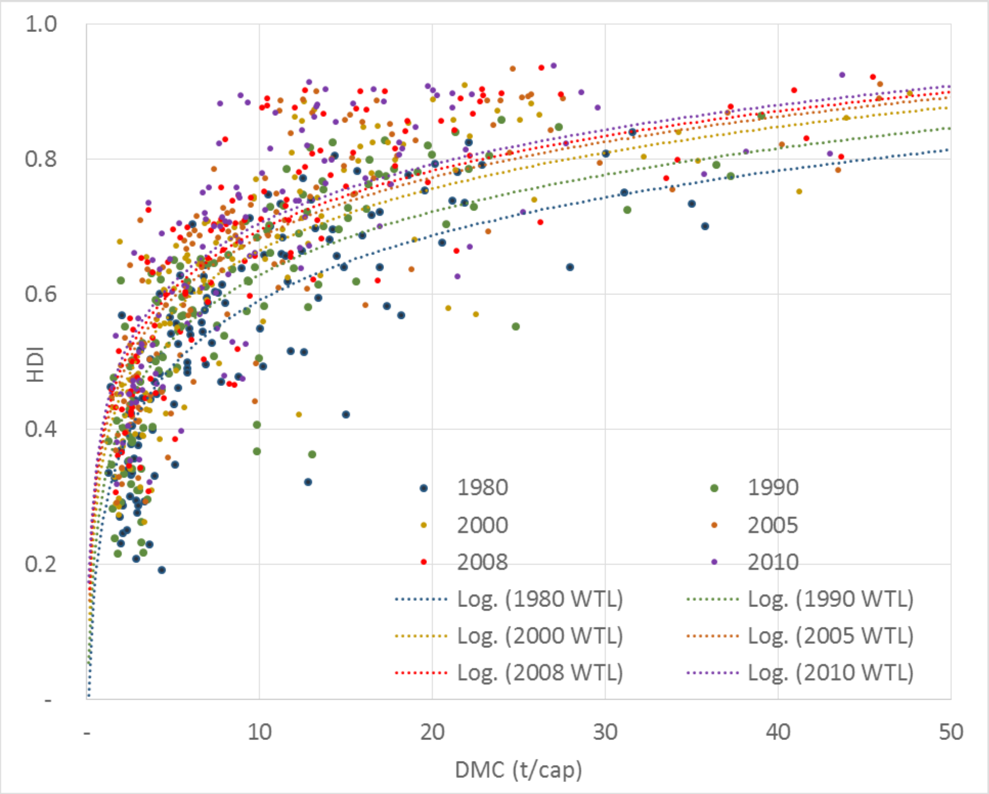


Figure 48. Relationship between per capita DMC and human development, 1980–2010

achieved for education, in part because once educational infrastructure is built, it continues to produce (educated people) for decades to come with relatively low additional inputs of materials and energy (largely for maintenance and operation). Even if the new output of educated

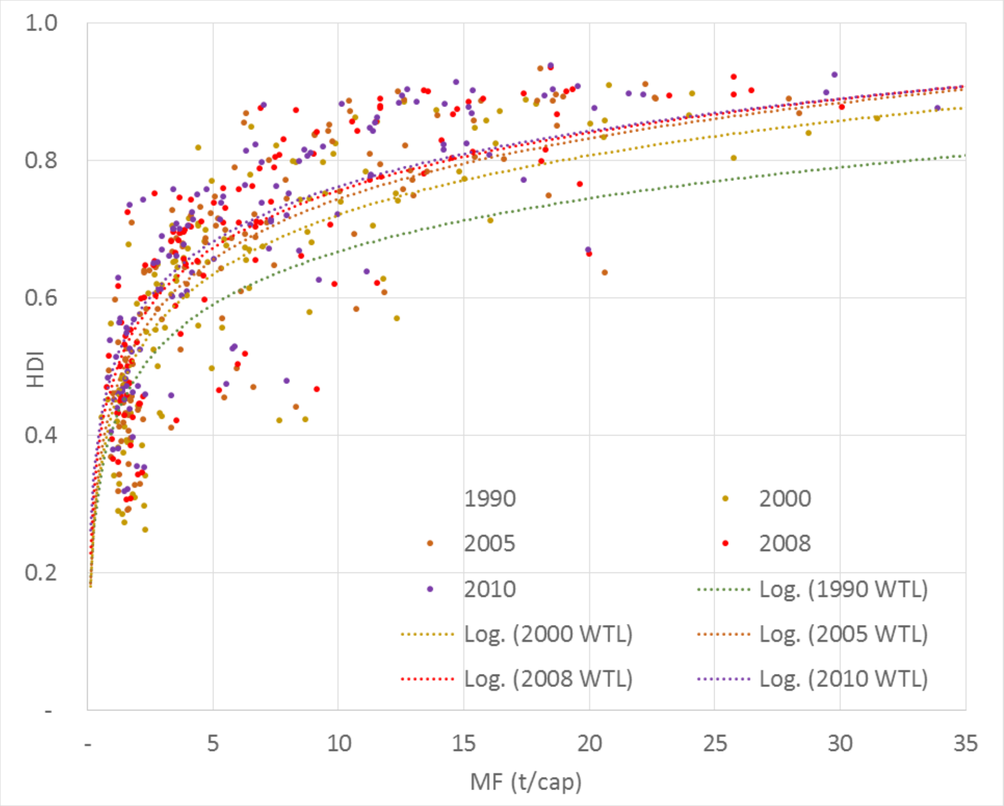


Figure 49. Relationship between per capita material footprint and human development, 1980–2010

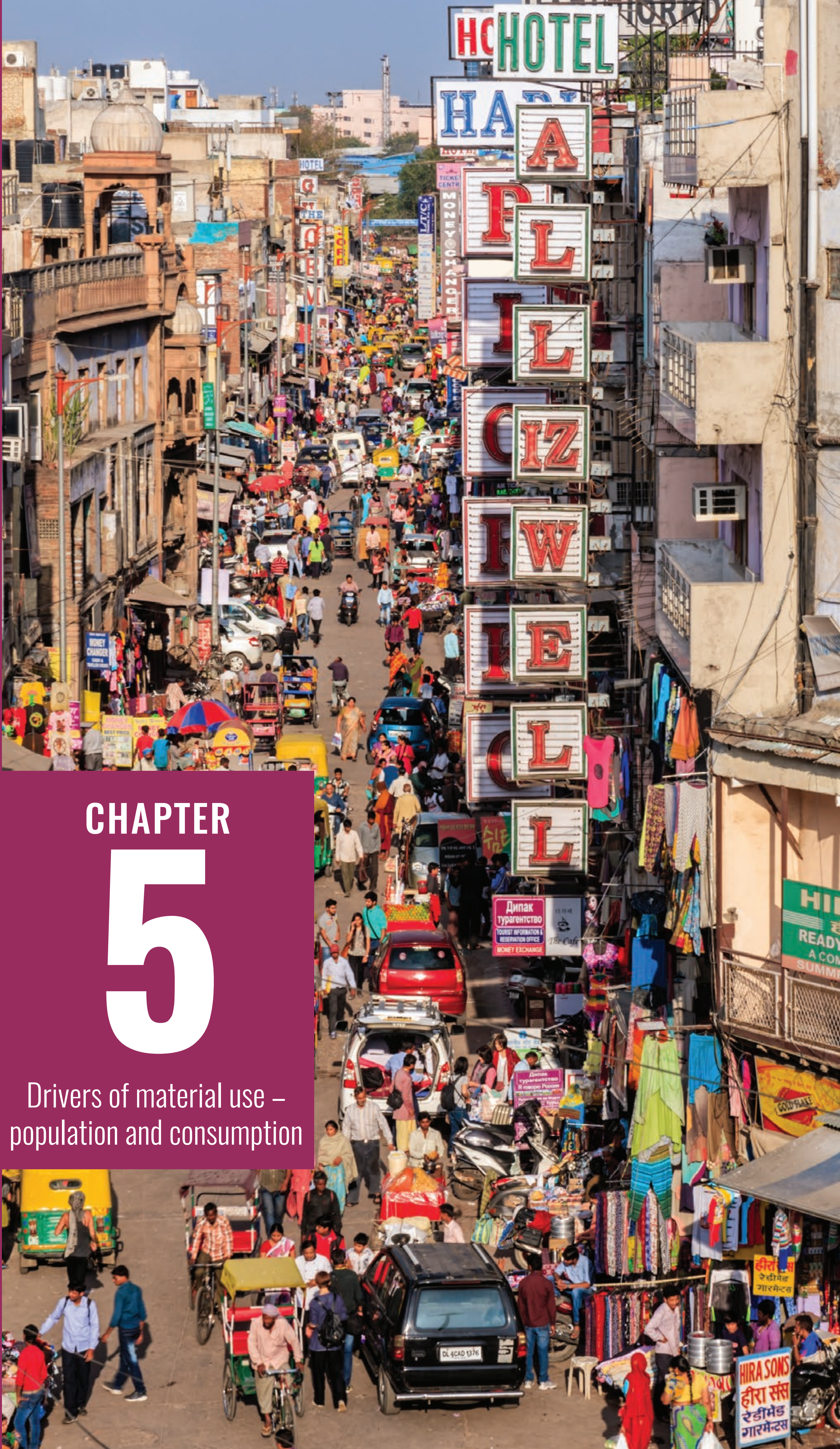
people remains roughly static as a proportion of population going forward, the average education level of the population stock should continue to increase for several decades, as the older, less educated generations die first. Similar effects occur for life expectancy, as the stock of people which have benefited from better health care over a longer period accumulates. In essence, in education and life expectancy we are looking at the evolution of stocks, whereas for income we are observing a flow.

The analysis shows that ongoing growth in income continues to rely on high inputs of material. It is noteworthy that the best result for income was achieved in 2008, in a situation where it has since become clear that financial markets were overvalued, artificially inflating the apparent growth in affluence. The GFC brought a correction, with results visible in the GNI results for 2010, where the per capita materials required for a given level of GNI revert to higher levels than seen for 2008.

To better understand the relationship of HDI to the physical economy, detailed accounts of the stock of physical assets that provide products and services to society are really required, but are not currently available. Our current level of knowledge is sufficient to suggest that ongoing improvements in life expectancy and education levels should continue to accumulate going forward, but that there is little indication that any fundamental decoupling of raw economic growth from material use has occurred. Furthermore, there is little reason to expect it to emerge in the context of how production and consumption systems are currently organized.

Drivers of material use – population and consumption

To better understand how material use has developed over the past four decades, and what trajectory it might take into the future, it is helpful to identify and analyse key drivers independently. One commonly used analytical framework to achieve this is the I = P x A x T equation (IPAT). This equation, which was originally proposed by Ehrlich and Holdren (1971), conceptualizes environmental impacts (I) as a product of population (P), the level of affluence of a



CHAPTER

5

Drivers of material use – population and consumption

nation (A), and a technological coefficient (T). As has been proposed in previous studies (Schandl and West 2010) we define I as material use (either domestic material consumption or material footprint), A as GDP per capita (US$ at 2005 constant prices), and T as material intensity (DMC/GDP or MF/GDP). To assess the relative contribution of individual drivers (P, A, T) we transform the IPAT equation to logarithmic form applying the methods established in Herendeen (1998).

Figure 50 to Figure 55 are constructed as follows: The left hand panel shows the overall change in the relevant impact (either DMC or MF) for the period indicated. The right hand panel then decomposes this net total change into the three individual components attributable to changes in each of P, A and T. The individual contributions attributed to P, A and T on the right hand side should add to the total on the left hand side to within a rounding error of 1 percentage point.

At the global level, material use grew in each of the four decades covered for DMC (Figure 50 to Figure 53), and in each of the two decades covered for MF (Figure 54 and Figure 55). The growth rate in DMC was slightly lower for each successive decade from 1970 to 2000 (37% growth from 1970 to 1980, 25% from 1980 to 1990, and 21% from 1990 to 2000), but accelerated between 2000 and 2010 (43% growth during that decade). Both population growth and rising per capita incomes acted to drive global material use higher in all four decades. In the 1970s and 1980s per capita income was the main factor driving material use higher, whereas in the 1990s affluence and population growth contributed almost equally[11]. Over the 10 years from 2000 to 2010 per capita income again become much more important than population growth, a development which should refocus attention on the importance of affluence and per capita consumption in driving increased resources use. The re-emergence of affluence as the key driver is a result of the accelerating industrial and urban transformation of countries like China, India and Brazil, among others. The new urban and industrial structures are characterized by much higher throughputs of fuel and energy than the traditional production processes and infrastructure they replaced.

In contrast to P and A, decreasing T acted to impede growth in materials use for the three decades from 1970 to 2000. After 2000 global material intensity began to increase, exacerbating rather than offsetting the effects of population and income in driving material use higher. This increase in global T came about even though T decreased for five of the seven world regions, the exceptions being the Asia-Pacific and West Asia regions. Given the very small contribution of West Asia to global DMC (2.3% in 2010), this indicates just how dominant the Asia-Pacific region has become in determining overall global resource use trends. Within the Asia-Pacific region, it has previously been established (UNEP 2011b) that the main driver of that region's increasing MI has been the greatly increased share of economic activity performed by the less resource efficient, higher MI countries of that region, especially China, at the expense of low MI countries, most notably Japan. It is important to recall that the phenomenon of share shifting can lead to increasing aggregate MI even when all nations involved improve their MI individually. That is was seen in the Asia-Pacific region, and it is entirely possible that had the Asia-Pacific's MI remained static or even decreased slightly, global MI would still have increased due to the shift

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[11] Note that the Global values used here have been calculated by weighting each region's contribution according to its regional resource use. The results are very different to those that are obtained using simple global aggregates for I, P, A and T. The latter method overstates the importance of population growth, by artificially creating undifferentiated "global consumers", with uniform A and T. This greatly exaggerates the influence that each extra consumer in poor regions has on total global consumption, and understates the impact of additional consumers in rich countries. As population growth is much faster in the poorest countries, a systematic and major overstatement of the importance of population growth ensues.

of economic activity away from more resource efficient regions like Europe and North America.

In Figure 50 we see that during the 1970s, the strongest driver of increasing DMC for six of the seven regions was A, the sole exception being Africa where P was almost twice as important. Africa's relatively low increase in A coincides with it being the region with the lowest increase in DMC for the decade. West Asia which had the largest contributions from both A and P, with only a minor offset from improved T, experienced a doubling in DMC. This coincides with the rapid increases in export income received by the many important petroleum producers in that region from the early 1970s on. The widespread improvements in T across all regions for the 1970s is also notable, and was probably largely the flipside of increasing oil prices, as increasing energy efficiency became a much more important priority for reducing production input costs.

The region with the most dynamic growth in material use in the 1980s was Asia and the Pacific (Figure 51). In relation to the other drivers, population growth continued to play an important role in Africa and Latin America and the Caribbean. Per capita income decreased in Africa and in Latin America due to the debt crisis of the 1980s and the decade of economic stagnation that followed (Ghai and de Alcántara 1990) induced a reduction of material use. In West Asia the decrease in A was much more severe, and resulted in the second slowest growth in material use (17%) of any region, despite continuing rapid population increases. West Asia's affluence decreased dramatically as a result of the collapse in oil prices from the early to mid-1980s. Increasing energy efficiency, substitution of other energy sources, and expanded non-OPEC oil extraction, all precipitated by the radically higher oil prices of the 1970s, and combined to drive the prices received for the region's main export sharply

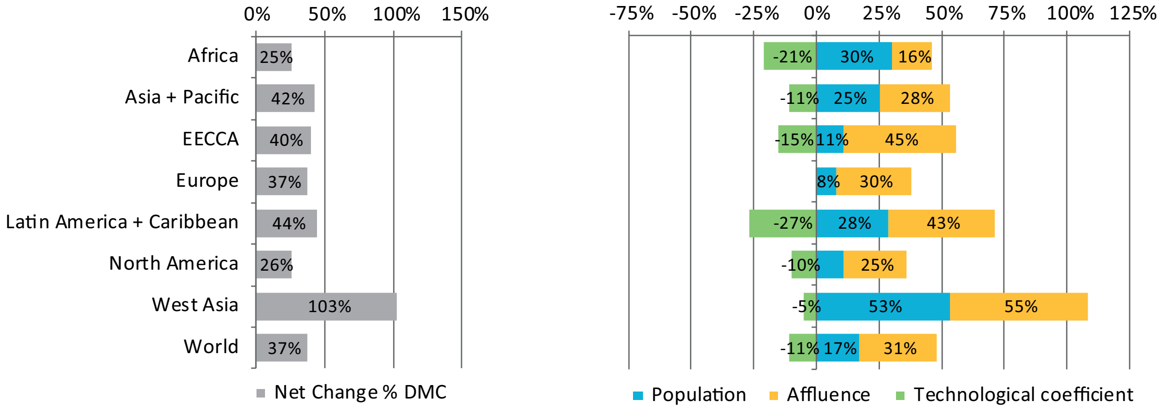

Figure 50. Drivers of net change in domestic material consumption between 1970 and 1980 for World regions: population, affluence and material intensity

lower. The strong growth in A and DMC seen for the Asia-Pacific region is at least partially attributable to the greatly reduced prices that Japan (then by far the region's major economy) had to pay for oil, its largest resource import. Improvements in material intensity were greatest in EECCA, Europe and North America but did not fully offset the other drivers of growth in material use in any region. In contrast to the 1970s where all regions improved material efficiency, Africa, Latin America and the Caribbean, and West Asia all experienced an increase in material intensity in the 1980s.

In Figure 52 we see the first signs of a turning point in the factors that drive global material use, with Asia and the Pacific becoming increasingly more material intensive. This change can be attributed to the early stages of the rapid urban and industrial transformation of China coinciding with the first decade of Japan's "lost two decades" of economic stagnation. Together, these two events began the major shift of the economic centre of the region away from the highly resource efficient Japan, towards China, a process that would accelerate greatly in the subsequent decade. Europe and North America continued to improve the material efficiency of their economies through structural change, outsourcing of material intensive production processes and to some extent through policy changes aimed at supporting resource efficiency and sustainable materials management.

The EECCA region experienced a very large decrease in national income during the political and economic restructuring which followed the dissolution of the former Soviet Union. The EECCA region's major improvement in material efficiency throughout the 1990s was driven by a number of dynamics. Many resource intensive and inefficient industries were forced to close due to their lack of viability in the absence of continued massive state support. Some of these industries had been run in extremely environmentally unsustainable and economically wasteful ways, leaving local

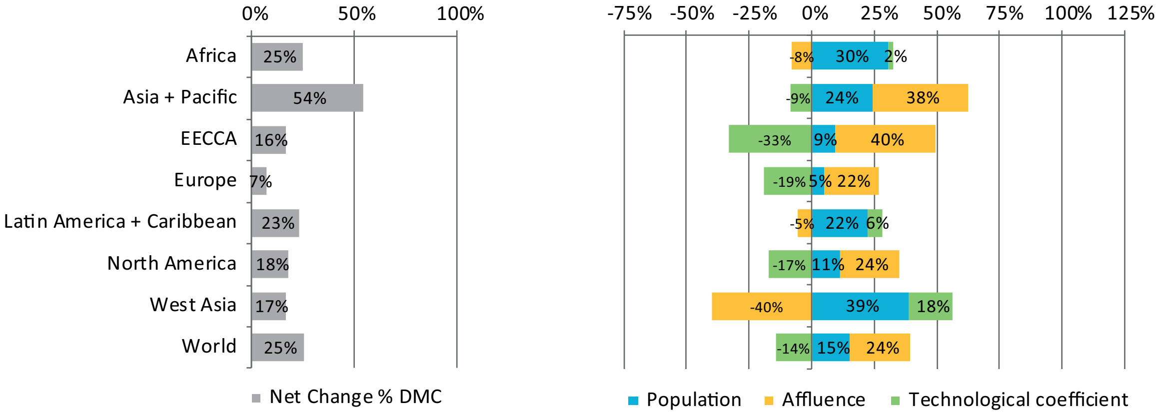

Figure 51. Drivers of net change in domestic material consumption between 1980 and 1990 for World regions: population, affluence and material intensity

resident populations hesitant to continue tolerating them. Furthermore, as the successor states opened further to international trade, alternative markets yielding higher prices for the raw materials previously used internally were exploited. The overall improvements in economic returns for these raw materials were in some cases augmented by ending what appears to have been widespread "negative value adding" in Soviet industry[12] (Simon 1996, Thornton 1996). This would also help explain how the EECCA region, even as it became a more commodity based economy, still experienced huge improvements in resource efficiency in a decade characterized by poor returns on primary commodities. This is not what we see for other regions with economies dominated by primary commodity exports.

For Africa, the 1990s were on average another decade of declining affluence, but population growth continued at a rapid pace, while MI simultaneously increased, so there was still a substantial increase (30%) in DMC. The increasing MI seen for Africa, Latin America, and West Asia can largely be attributed to the 1990s being a decade of poor and deteriorating prices for many primary commodities. Despite the generally poor outlook for commodity prices for much of the 1990s, Latin America still fared relatively well compared to the preceding decade with regard to increasing affluence and material standards of living, largely as major economies there rebounded from the debt crisis of the 1980s.

Europe's very minor increase in I was roughly proportional to population increase, with decreased MI offsetting virtually all of the growth in DMC that would otherwise have accompanied its increasing A. This continued a pattern established in the preceding decade, and indicates a pattern of entrenched relative decoupling/dematerialization, *when using DMC per capita as the metric for I*. As we will see below, this is not nearly as clear a trend when using MF for I instead.

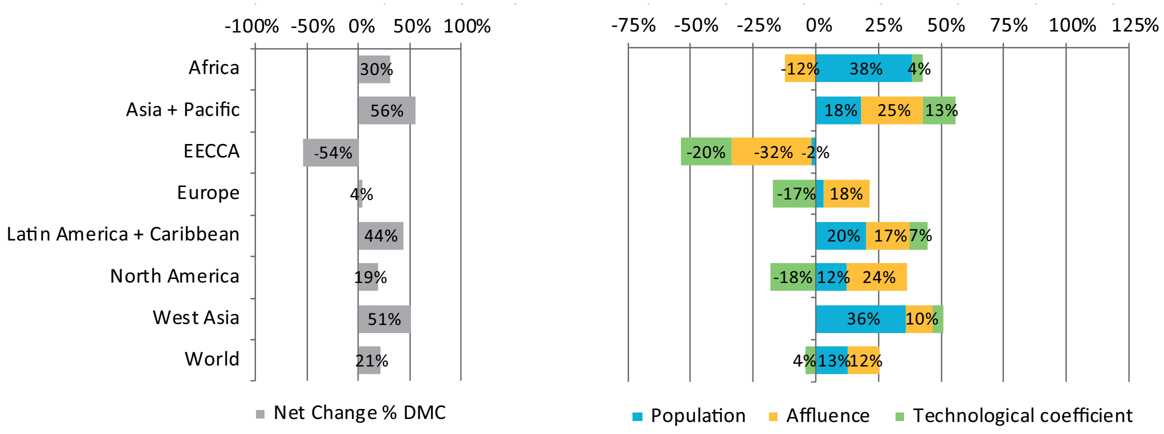

Figure 52. Drivers of net change in domestic material consumption between 1990 and 2000 for World regions: population, affluence and material intensity

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[12] Negative value adding refers to the situation where the value of the inputs and components used in a production process are worth more than the resulting final product.

In Figure 53 we see that the accelerating urbanization and industrialization of the Asia-Pacific region's developing economies greatly increased A there, and also drove major increases in MI as the economic centre of gravity shifted further towards less resource efficient economies. The deterioration in aggregated MI for the region is such that it becomes the second strongest driver of rapidly growing DMC there, replacing population. It should be remembered that this increase in regional MI came despite most countries, including all of the largest economies, decreasing their individual MI. In this period the region begins to dominate global material use, with its strong growth in DMC taking the global aggregate to its highest level in any of the four decades, despite the contractions in DMC seen for both Europe and North America in the wake of the GFC.

There is a strong rebound in A for those regions most closely associated with dependency on natural resource exports, reflecting the massive increases in primary commodity prices which characterized the decade, a result of the huge increase in demand from the Asia-Pacific region, led by China. Latin America's affluence increases more strongly than in any decade since the 1970s, while Africa displays its strongest increase in A of any decade. In both cases, increasing A had become a more important driver of DMC growth than P. In the case of Africa, this was for the first time. Only in West Asia did P remain the major driver of DMC growth.

Figure 54 and Figure 55 report on the drivers of material use between 1990 and 2010, using MF as the indicator for I in place of DMC, and AMI as the indicator for T rather than MI. By taking the embodiment of upstream material inputs into account (as discussed previously in Chapter 3), using footprint based measures provides a very different perspective on both the relative growth in material consumption for different regions, and on the drivers behind that growth.

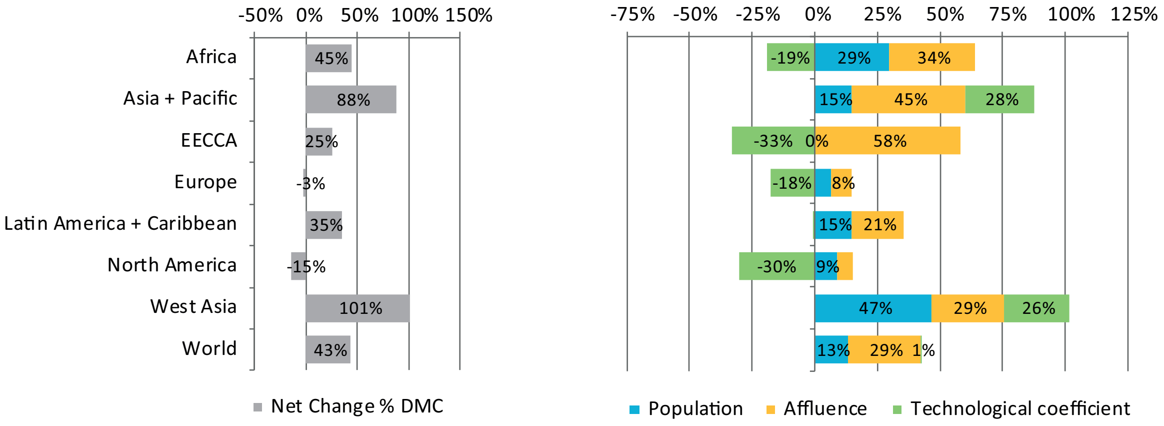


Figure 53. Drivers of net change in domestic material consumption between 2000 and 2010 for World regions: population, affluence, and material intensity

In Figure 54, we see that for the 1990s, growth in I was broadly comparable for four of the regions, with Europe, Latin America, North America, and West Asia all increasing MF by between 33% and 39% over the decade. This contrasts with what we saw in Figure 52, and indicates a systematically higher estimate for the two industrialized regions, and lower for the developing / primary commodity exporting regions. The tendency to reduce the consumption attributed to commodity exporters is further confirmed when we compare Figure 52 and Figure 54 for Africa and EECCA, with the decrease in MF for EECCA being a remarkable 75%. This is indicative of a large drop in material living standards, notwithstanding the great improvements in efficiency with which the EECCA region began to use those resources it continued to consume.

If we now compare the drivers sections of Figure 52 and Figure 54, the strongly decreasing MI seen previously for North America and Europe now ranges from near static (North America) to moderately increasing (Europe) AMI. This is consistent with what we would expect to see if the relative decoupling we saw for both regions using MI, is actually a result of offshoring materials and energy-intensive processes to other regions, rather than really reducing the need for such operations to be performed. The consumption of these two regions embodies a large quantity of materials and energy which was input to production extra-territorially. The flip side of this is seen in the drivers for the primary materials exporters, all of which show a considerable decrease in AMI relative to MI. For Africa and West Asia, the change is such that they show significant relative decoupling on the AMI metric. The already very strong relative decoupling seen for the EECCA region using MI becomes truly remarkable using AMI, although absolute decoupling could still not be said to have been achieved, as the economy contracted. The smallest changes are seen for the Asia-Pacific region. This is probably a result of it being such a diverse region, encompassing both very high-income and very poor nations, as well as advanced manufacturing / service based economies and primary export based economies.

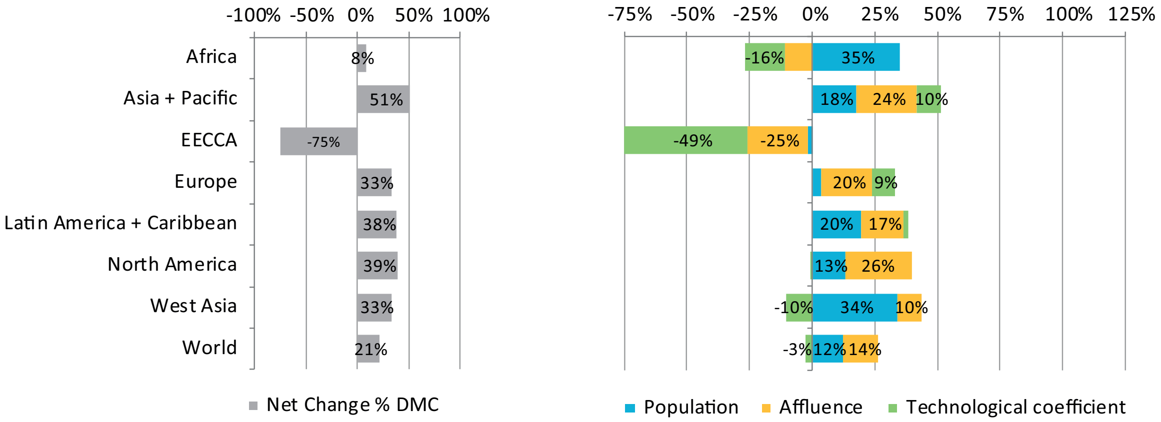


Figure 54. Drivers of net change in material footprint between 1990 and 2000 for World regions: population, affluence and material intensity

Comparing Figure 55 to Figure 53 is useful in illustrating the degree to which footprint based measures reallocate primary materials use to their point of final consumption. The GFC affected North America and Europe far more strongly than it did the other regions. Consequently, consumption in those two regions decreased relative to other regions. As a result, MF for both regions contracted over the course of the 2000s, whereas for MI it only contracted for North America (and by much less). The reductions in MF for these two regions have been reattributed to all other regions, which all show increased MF compared to DMC, with the exception of the EECCA region. The effects of this redistribution on other regions is relatively modest in most cases, with Africa, the Asia-Pacific and Latin America all showing MF increasing a few per cent more than DMC. The largest relative increase was for West Asia.

In comparing the drivers sections of Figure 53 and Figure 55, we see that the effect of including embodiment of upstream materials in AMI works in reverse when consumption decreases. Where Europe and North America strongly improved their MI in the wake of the GFC, that improvement is even stronger when we use AMI, as all of the materials embodied in foregone consumption are removed from these regions' footprints. In contrast, the AMI for all other regions except the EECCA region increased, usually marginally but in the case of West Asia quite strongly. For West Asia, this result was most likely driven by the huge increases in export incomes it received from exports of petroleum, and the increased consumption that permitted.

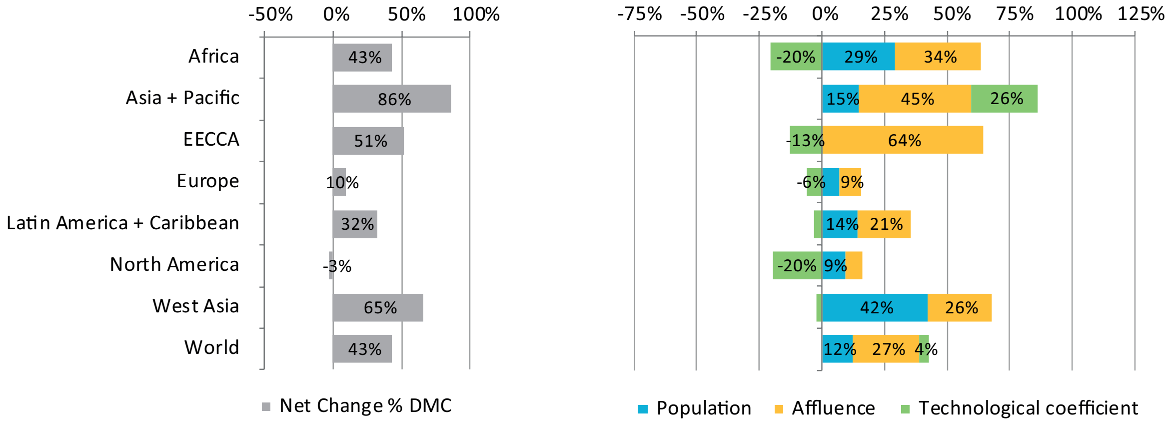


Figure 55. Drivers of net change in material footprint between 2000 and 2010 for World regions: population, affluence and material intensity

CHAPTER

6

Country Profiles

Country profiles

National Panels for: Australia, Bangladesh, Brazil, Chile, China, Egypt, France, Germany, Guatemala, Honduras, India, Indonesia, Iran, Iraq, Japan, Kazakhstan, Mexico, Nigeria, Pakistan, Poland, Russian Federation, Saudi Arabia, South Africa, South Korea, United Kingdom, United States, Viet Nam.

AUSTRALIA

The indexed summary indicators show rapid growth of GDP compared to population, indicating strong growth in affluence over the period 1970 to 2010. In contrast, DMC grew more rapidly than GDP for much of the period, indicating declining material productivity until the growth trend in DMC became much slower beginning around 2000. The new trend led to material productivity finally exceeding 1970 levels from 2005 on. These late improvements in material productivity were not reflected in any significantly decrease the growth rate of Australia's MF, which continued on a similar trend both before and after 2005. Per capita DE for Australia began the period very high even for the VHDI group to which it belongs, then continued to grow at a very rapid rate, unlike the VHDI group as a whole. The contrast with its group in is strongest in the new millennium, and can be explained by its trade integration with the rapidly growing economies in the HHDI group, above all China. It similarly diverges greatly from its group in PTB per capita, with consistent strong increases in net exports across the period, accelerating markedly from 2005, and is similarly starkly different in RTB, with strong growth in net embodied exports off a very high base, the inverse of the VHDI group's pattern. Australia is much closer in general profile to the VHDI group in DMC per capita, although at much higher levels, and lacking the sharp decline since 2007. Australia's MF per capita profile is the most similar to its group, in both general profile, and in absolute tonnages per capita, (with Australia generally around 50% higher).

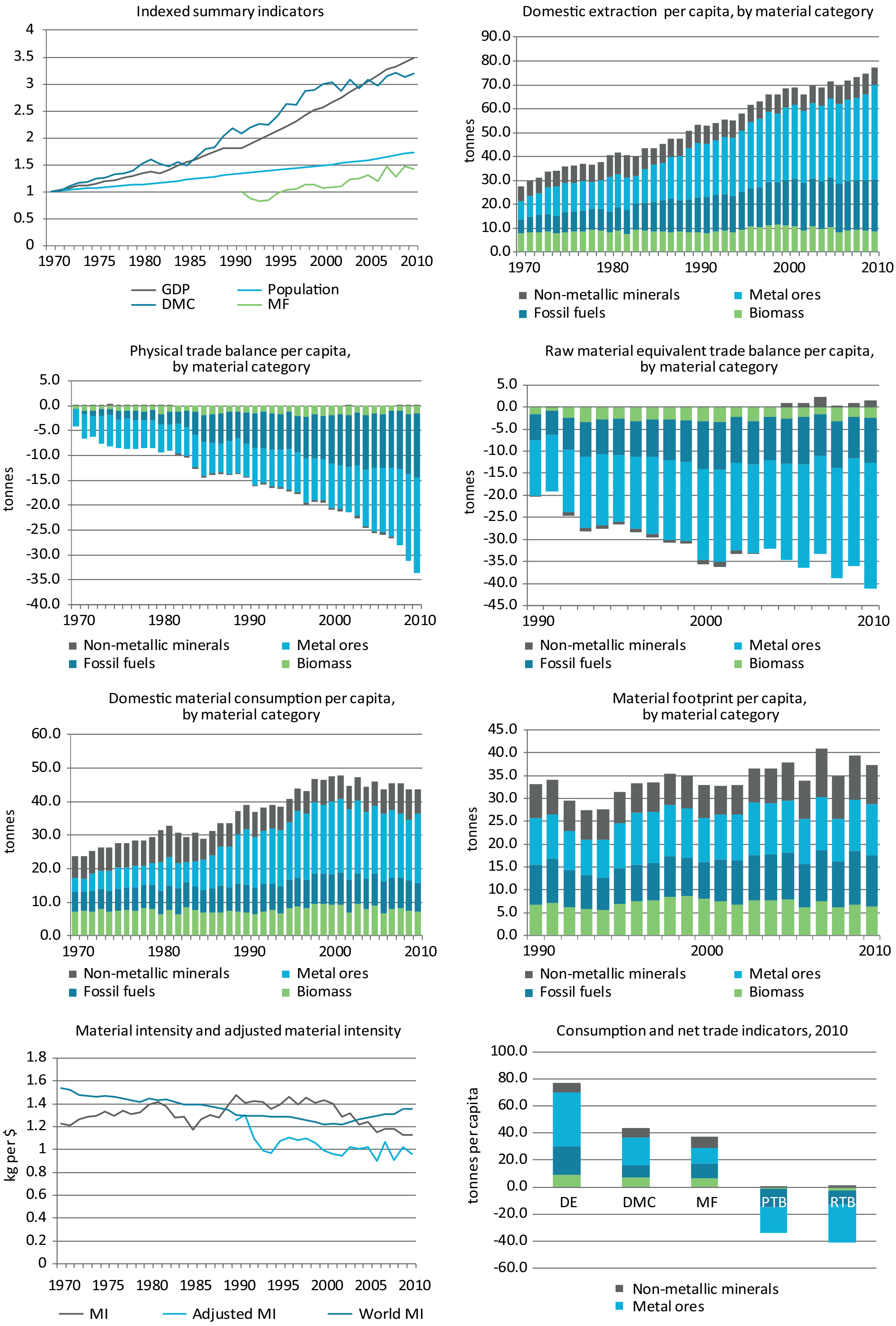


Figure 56. Australia

BRAZIL

The indexed summary indicators for Brazil show a similar close coupling between GDP and DMC to that seen above for Australia, although growth rates in both were considerably stronger over the period, increasing approximately fivefold. As a consequence, Brazil's material productivity also only recently began to exceed levels attained in 1970. Population doubled, with a marked slowdown in growth from 2005, roughly contemporaneous with a major increase in growth of DMC and MF, indicating rapidly increasing DMC and MF per capita. Unusually, Brazil's growth in DE and DMC per capita was dominated by biomass, in absolute tonnage terms, although all categories grew strongly in percentage terms, with non-metallic minerals growing by over 550% over the full period. PTB shows that much of the rapid increase in DE of metal ores when into increasing exports, which dominated the change in Brazil's PTB per capita status, from being nearly balanced in net terms to having nets exports (in metal ores and biomass) a factor of ten greater than net imports (of fossil fuels and non-metallic minerals). In RTB terms, the same materials dominate net imports (fossil fuels and non-metallic minerals) and net exports (metal ores and biomass), although the ratio between net imports and exports is much closer, at approximately 1:2 rather than 1:10. Interestingly, Brazil's total DE profile is very close in both general form, and in magnitude, to the pattern shown for the HHDI group of countries, although this match would not hold for individual material categories, especially biomass. Brazil's total DMC and MF in 2010 were within 6% of each other, with the greatest difference for metal ores and fossil fuels, where MF was approximately 40% higher than DMC for both.

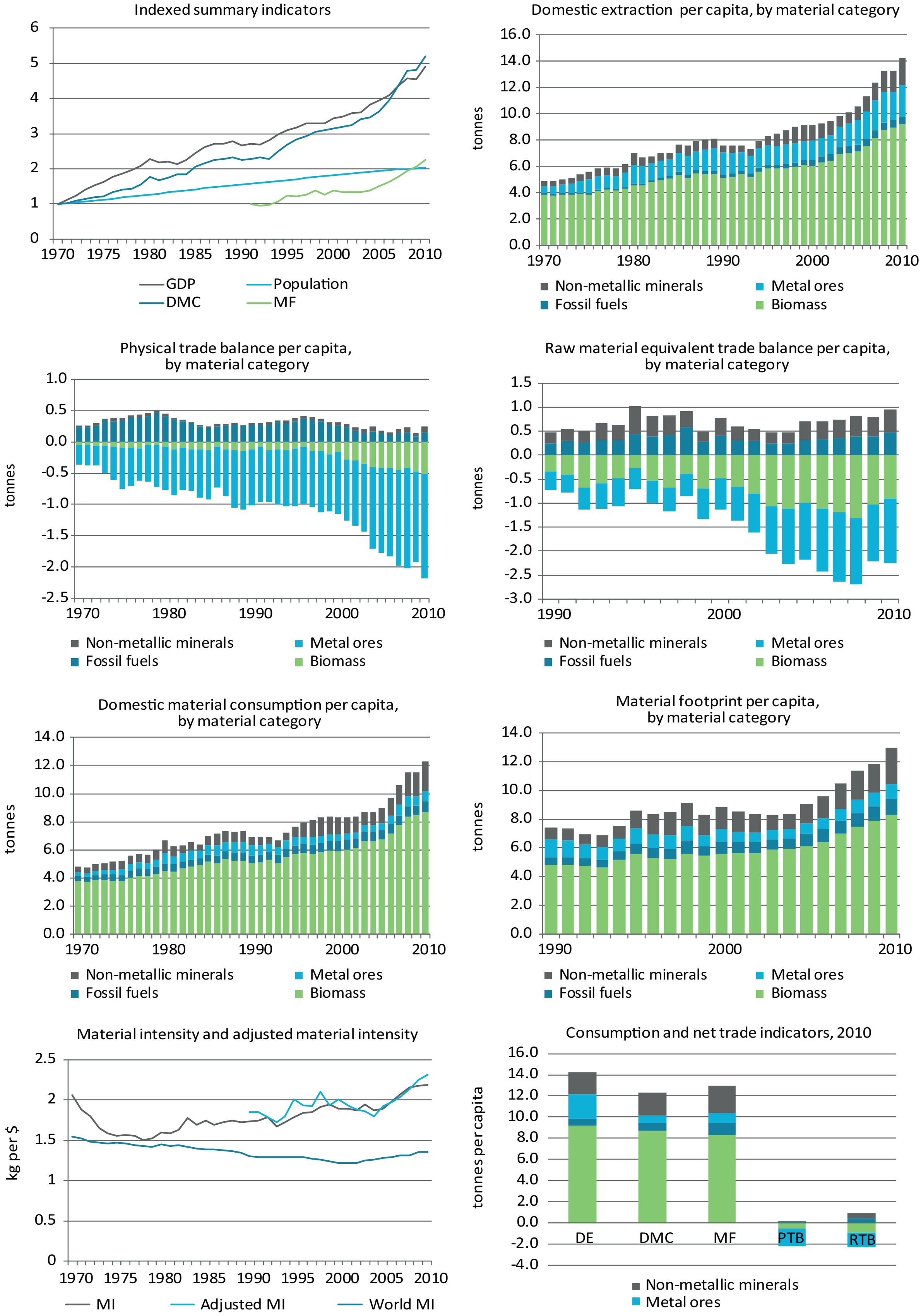


Figure 57. Brazil

CHILE

The indexed summary indicators for Chile show a rapid growth in affluence from 1970 to 2010 (GDP > population), and a strong deterioration in material productivity (GDP < DMC), although growth in DMC began slow from the late 1990s, while DMC growth continued to be strong, so material productivity is improved over the final decade. DE grew very rapidly until 2000, dominated by metal ores, then stabilized for most of the final decade, at a very high level for a HHDI country of roughly 43 tonnes per capita. PTB shows net imports dominated by fossil fuels, with a general form similar to that seen for DE of metal ores. This would be consistent with a large portion of the country's fossil fuels being consumed in mining activity. While metal ores are the largest component of net exports, they do not dominate PTB to anything near the extent seen for DE. This is due to the high concentration of copper ores prior to being internationally traded, with mine wastes attributed to Chile's DMC account. The contrast with RTB is stark, where most of the ore embodied in Chile's huge copper exports is included in addition to the concentrated commodity that is physically exported, and so approximates a mirror image of DE (and DMC) for metal ores. The contrast between Chile's apparent consumption using DMC, and its real consumption after taking materials embodied in trade into account, is made clear in the side-by-side comparisons for 2010, with DMC over twice MF, and net exports using RTB are an order of magnitude higher than when using PTB.

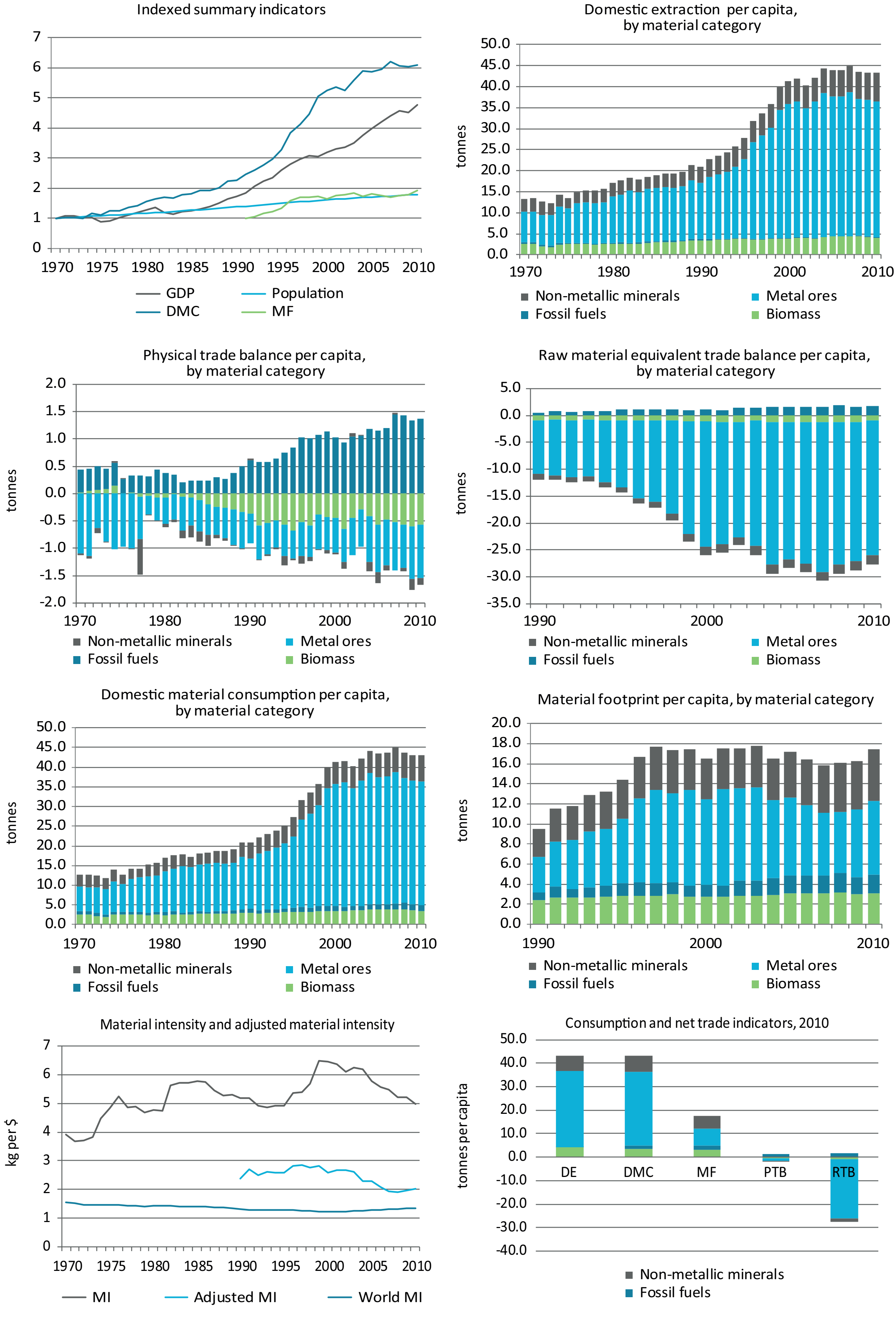


Figure 58. Chile

CHINA

The indexed summary indicators for China show a very rapid growth in affluence from 1970 to 2010 (GDP >> population), with strong improvements in material productivity (GDP > DMC), although nowhere near strong enough to avoid an extremely large increase in total DMC, which increased 13 fold. The trajectory of PTB has some notable features. The first is the change from something near self-sufficiency in all things in 1970, to a strong dependence on net imports of fossil fuels and metal ores by 2010. The second feature is the major step up in 2009 and 2010, which reflects the additional inputs required by the massive economic stimulus implemented by the Chinese Government at this time, to avoid the negative flow-on effects from the GFC, which reduced the capacity of China's major import markets to continue to buy China's industrial output. The continued strong growth of GDP in 2009 and 2010 would indicate that the stimulus served its immediate purpose. We also see the effects of the GFC/stimulus succession reflected in RTB, where China's net exports of embodied materials rapidly decrease from 2008, even as MF continues to grow strongly. This indicates some reorientation of economic activity away from an export focus, towards domestic investment and consumption. Even in the wake of this reorientation, relationship between PTB and RTB (in the consumption and net trade indicators) show that in 2010 China was still exporting, in net terms, more primary materials in embodied form than it was importing directly in physical form. The small relative size of PTB compared to DE also indicates the degree to which China is still largely self-sufficient, even given the large relative increases which took place in PTB between 1970 and 2010.

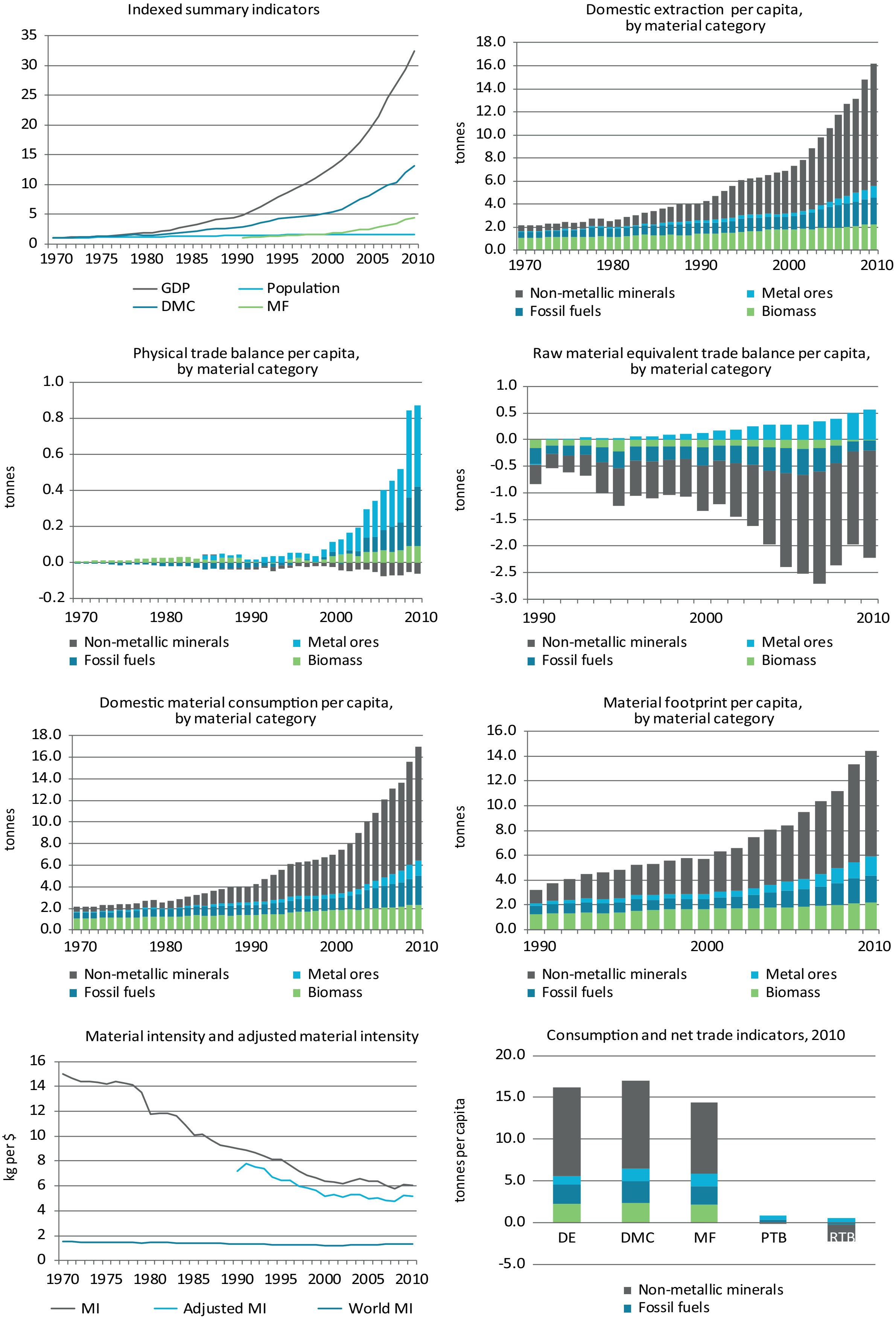


Figure 59. China

EGYPT

Egypt's GDP growth was high for its MHDI group, while population growth was average, giving a better than average improvement in affluence. DMC increased at around half the rate of GDP, indicating a slightly higher level of relative decoupling compared to the group average, however absolute DMC increased almost by over 400%, faster than the group average (under 300%). DE and DMC both reflect an ongoing trend increase in the minerals share compared to biomass, indicative of steady industrialization. Growth in DMC was dominated by non-metallic minerals in absolute terms, but DMC of fossil fuels also grew strongly in percentage terms (just under 300%). PTB indicates that Egypt is consistently dependent on moderate net imports of biomass, and was been a consistent exporter of fossil fuels, although this latter decreased strongly from the mid-1990s and in 2010 remained around one third the peak level of 0.47 tonnes per capita, attained in 1985. Using the RTB metric, Egypt is a net exporter of embodied materials in all categories except metal ores. Major decreases in MI were achieved in the two decades to 1990, from which point MI has remained largely static, a trend mirrored in adjusted MI.

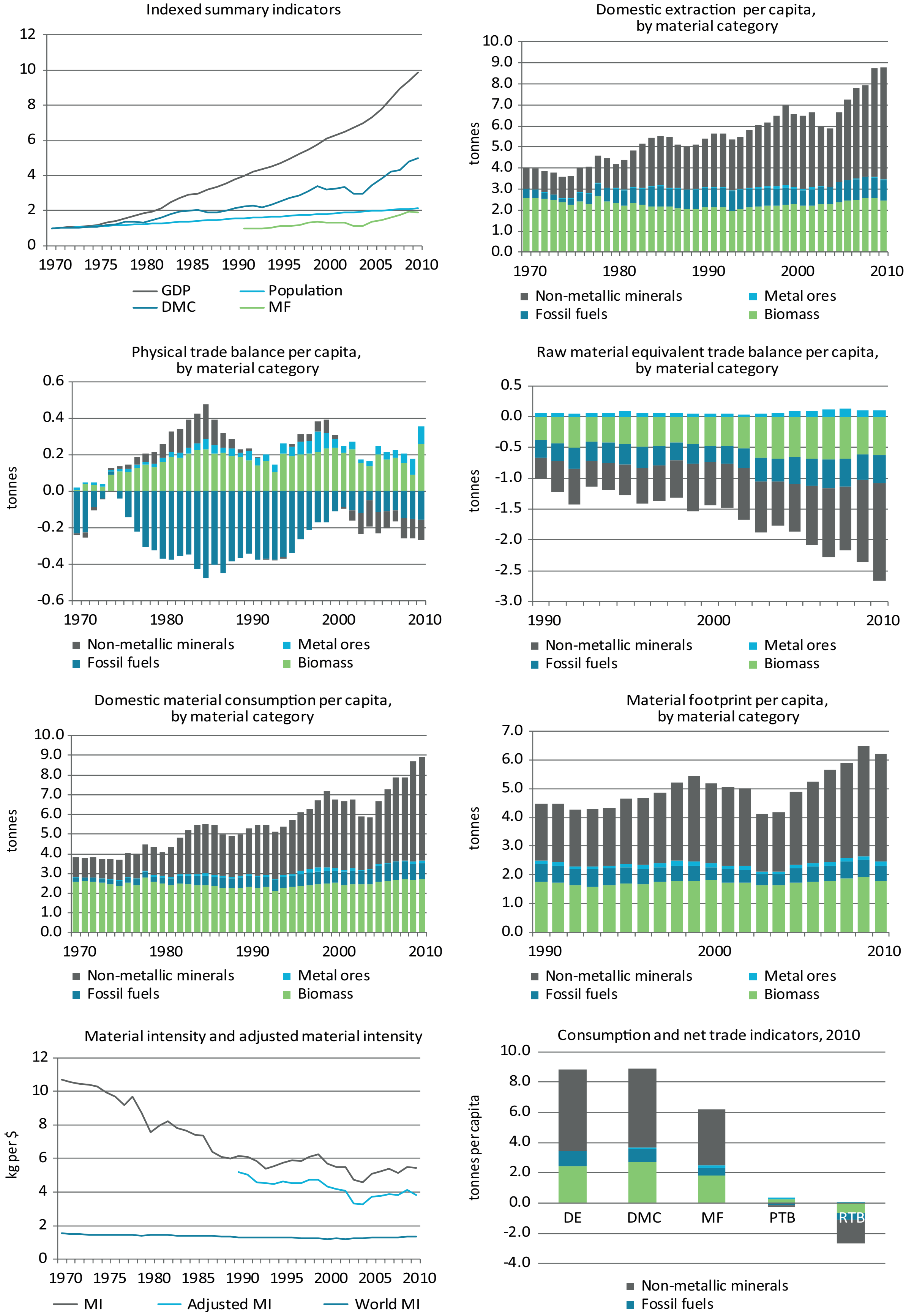
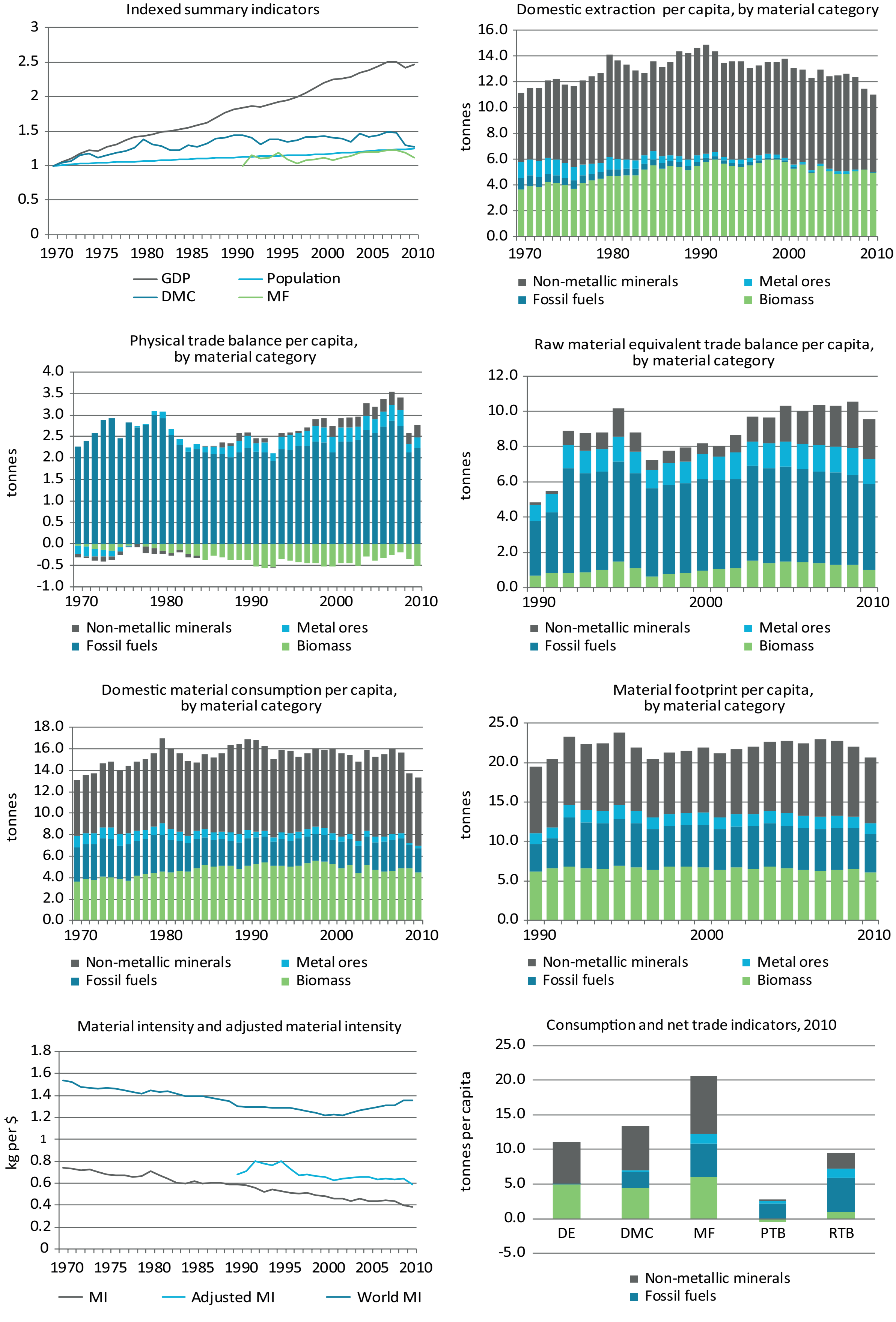


Figure 60. Egypt

FRANCE

The indexed summary indicators for France indicate strong relative decoupling of GDP from DMC, although as both were higher in 2010 than 1970, absolute decoupling was not achieved. The re-convergence of DMC and population by 2010 indicates that France managed to return to the same level of DMC per capita it had in 1970, despite a doubling in affluence of its people. DE in 2010 had returned to almost the same level as 1970, after peaking in the 1990s, despite a small increase in population. The composition of DE shows that the French economy has become almost totally reliant on imports for any inputs of metals or fossil fuels, a situation reflected in the dominance of PTB by fossil fuels. France imports around twice as much of its fossil fuels in embodied form, as indicated by RTB, and five to ten times as much of its metal ore requirements. Total PTB has a similar form to that for the VHDI group as a whole, but at a level two to three times higher. RTB is also similar in form to VHDI group RTB, but increases less over time so that by the 2000, Frances RTB is only 20–30% higher than the VHDI average. DMC and MF patterns are also similar in form and magnitude to VHDI averages. In 2010 DMC was only two thirds MF per capita, while PTB was less than a third of RTB, and showed France as being reliant on net imports of materials in all four categories once embodiment was taken in to account. Nevertheless, both MI and adjusted MI improved over the period.



Indexed summary indicators

Domestic extraction per capita, by material category

Physical trade balance per capita, by material category

Raw material equivalent trade balance per capita, by material category

Domestic material consumption per capita, by material category

Material footprint per capita, by material category

Material intensity and adjusted material intensity

Consumption and net trade indicators, 2010

Figure 61. France

GERMANY

The indexed summary indicators for Germany show a strong growth in affluence (GDP > population) over the period, with GDP more than doubling while population remained almost static. A strong relative decoupling was also achieved, and since the late-1990s DMC began declining despite continued growth in GDP, so that a period of modest absolute decoupling appears to have prevailed in the new millennium. Total DE per capita finished the period at almost exactly the same level as it started, however the mix of materials was much changed, with fossil fuel extraction decreasing by almost two thirds, while biomass doubled. The major decrease in fossil fuel extraction came in the decade following 1989. Even after this fall in fossil fuel production, Germany still met around one half of its fossil fuel requirements from DE, and the other half via net imports as shown in PTB. Interestingly, on the RTB measure Germany receives only slightly more fossil fuels in embodied form than it gets in through net physical imports. This is not true for biomass and metal ores, where in 2010 it received respectively 13 times and three times as much in embodied form as it did in net physical imports. MF was 27% higher than DMC in 2010, and around two tonnes per capita lower than VHDI average. The decoupling discussed above is evident using both the MI and adjusted MI metrics.

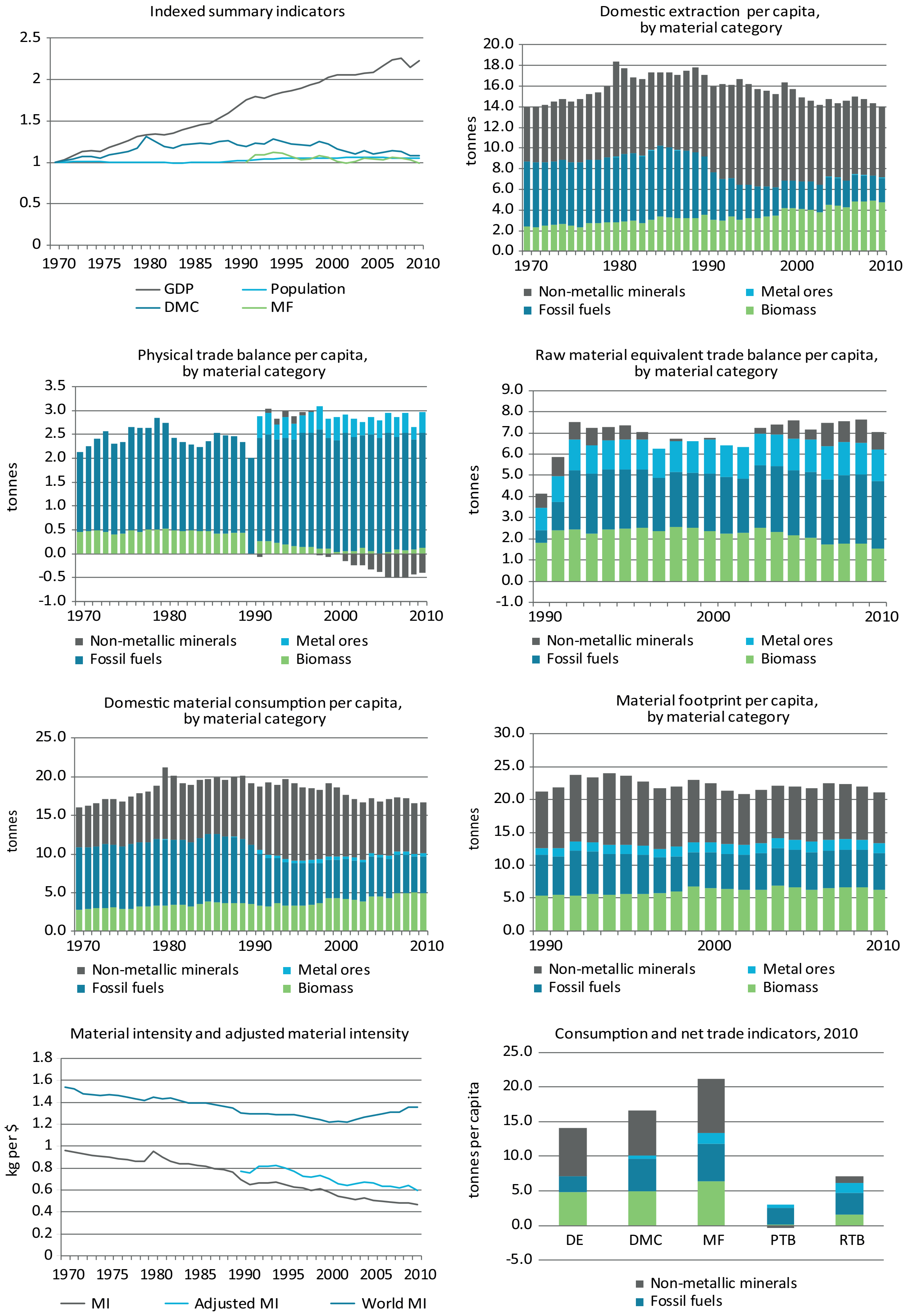


Figure 62. Germany

HONDURAS

In Honduras, a period of moderate relative decoupling between GDP and DMC ended in the mid-1980s, since which time growth in GDP has required a roughly proportional increase in DMC. Population growth has been faster than the average for its MHDI group, while GDP growth around 30% slower, so affluence only improved at around one third the rate of its group. DE has seen a major decrease in both the share, and the absolute tonnage per capita of biomass, with a major increase in non-metallic minerals. This is also reflected in DMC, with marked growth in fossil fuels as well, of a very low initial base. PTB shows a growing per capita dependence on imported fossil fuels, while net exports of biomass of around 0.4 tonnes per capita in 1970 steadily decrease to zero before around 2005. This change in physical trade is not reflected when embodiment is taken into account, with RTB indicating consistent net exports of biomass of 1 to 1.8 tonnes per capita for the entire period, while requiring small net imports in all mineral categories in most years. MI remained static from the mid-1980s, with a similar trend for adjusted MI from 1990. In 2010 DMC overstated consumption by 40% relative to MF.

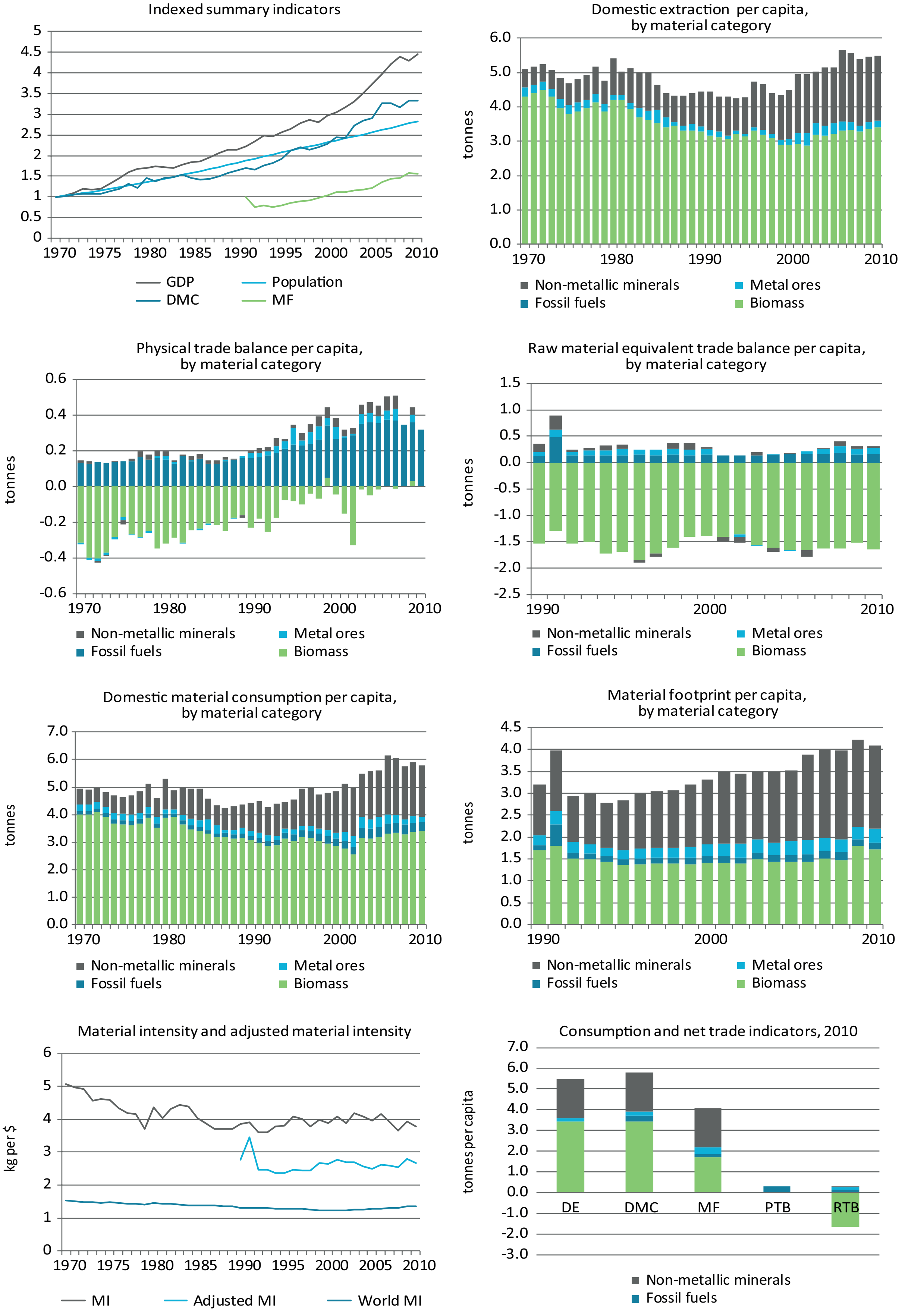


Figure 63. Honduras

INDIA

The indexed summary indicators for India show a strong growth in affluence over the period, especially from around 1990, where population continued to increase in a roughly linear trend while GDP grew at a compounding annual rate of 6.5%. DMC grew at 4.2% compounding from 1990 on, which saw DMC double in less than two decades, but nonetheless indicates quite strong relative decoupling. The time series for both DE and DMC provide a very clear example of the change in relative shares of different materials expected as a nation begins the transition from advanced agrarian society to industrialized, with biomass per capita nearly static, and the three mineral categories (fossil fuels, metals, and non-metallic minerals) all increasing rapidly. PTB shows a very rapid increase in net fossil fuel imports has been necessary as the transition has progressed, despite DE in this category quadrupling between 1970 and 2010. RTB indicates that despite increased net physical imports, India is a net exporter of embodied materials in all categories. Material productivity has increased strongly and consistently on both MI and adjusted MI measures.

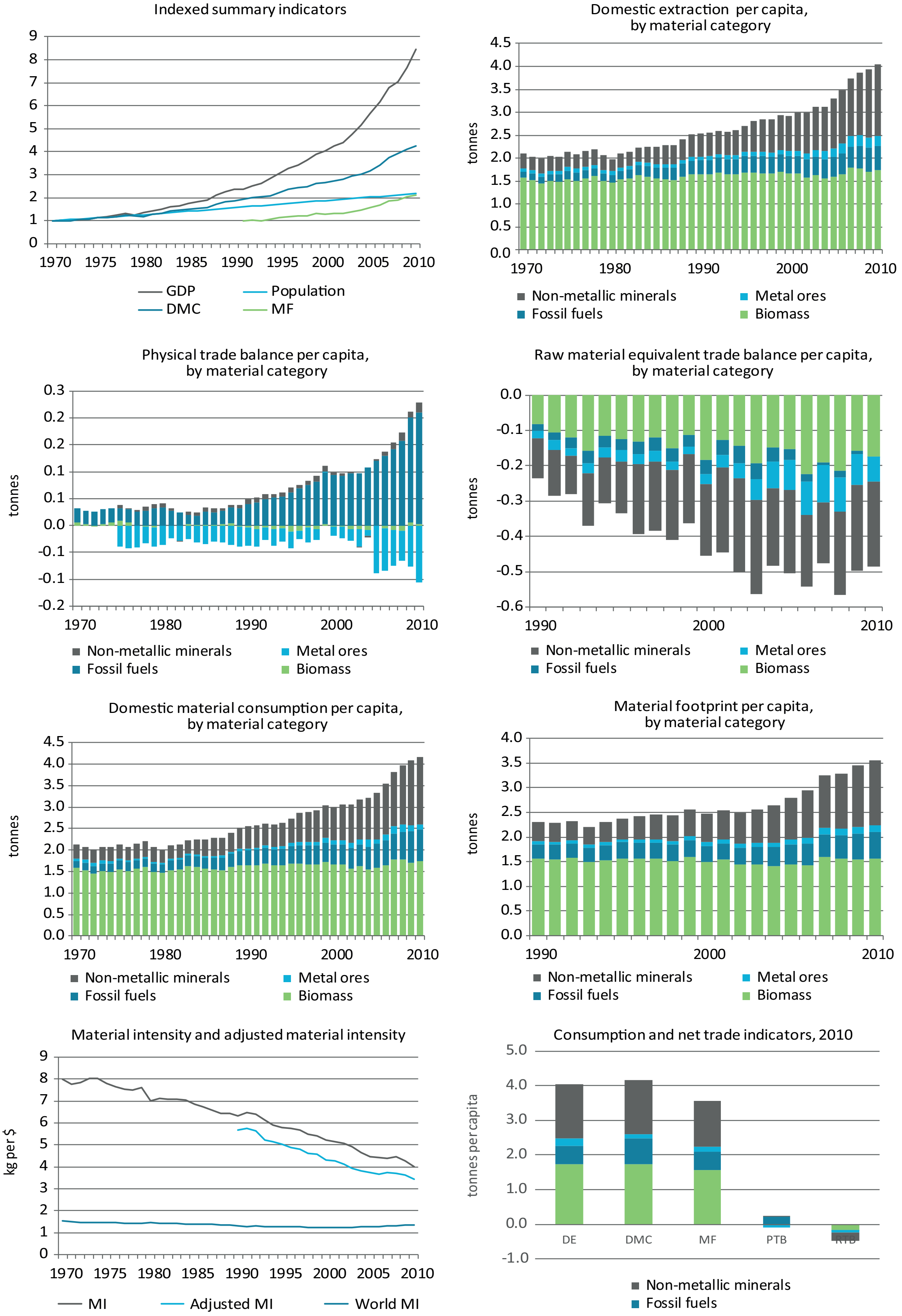


Figure 64. India

INDONESIA

The indexed summary indicators for Indonesia show a strong growth in affluence over the period, with one period of reversal when GDP fell in the immediate aftermath of the Asian financial crisis in 1997. That event also seems to roughly coincide with the end of a period of strong relative decoupling; where GDP grew at over twice the rate of DMC between 1970 and 1997 (6.9% and 3.1% compounding, respectively), from 1998 to 2010 the rates were comparable (2.6% versus 2.5%). DE shows the expected pattern of a socio-metabolic transition, similar to that noted previously for India, another large MHDI country, but from PTB we see that some of this was being directed to increasing net exports, especially of fossil fuels, a very different pattern to that for India. RTB shows that in addition to growing direct exports of fossil fuels, much of the rapid increases in DE of metal ores is embodied in its exports, something that is not clear from PTB. MI shows that the period of strong relative decoupling actually ended around 1994, somewhat before the Asian financial crisis, however from adjusted MI 1998 would better define the end of relative decoupling. DMC was a third higher than MF in 2010, while RTB indicated net embodiment of exports was twice net physical exports.

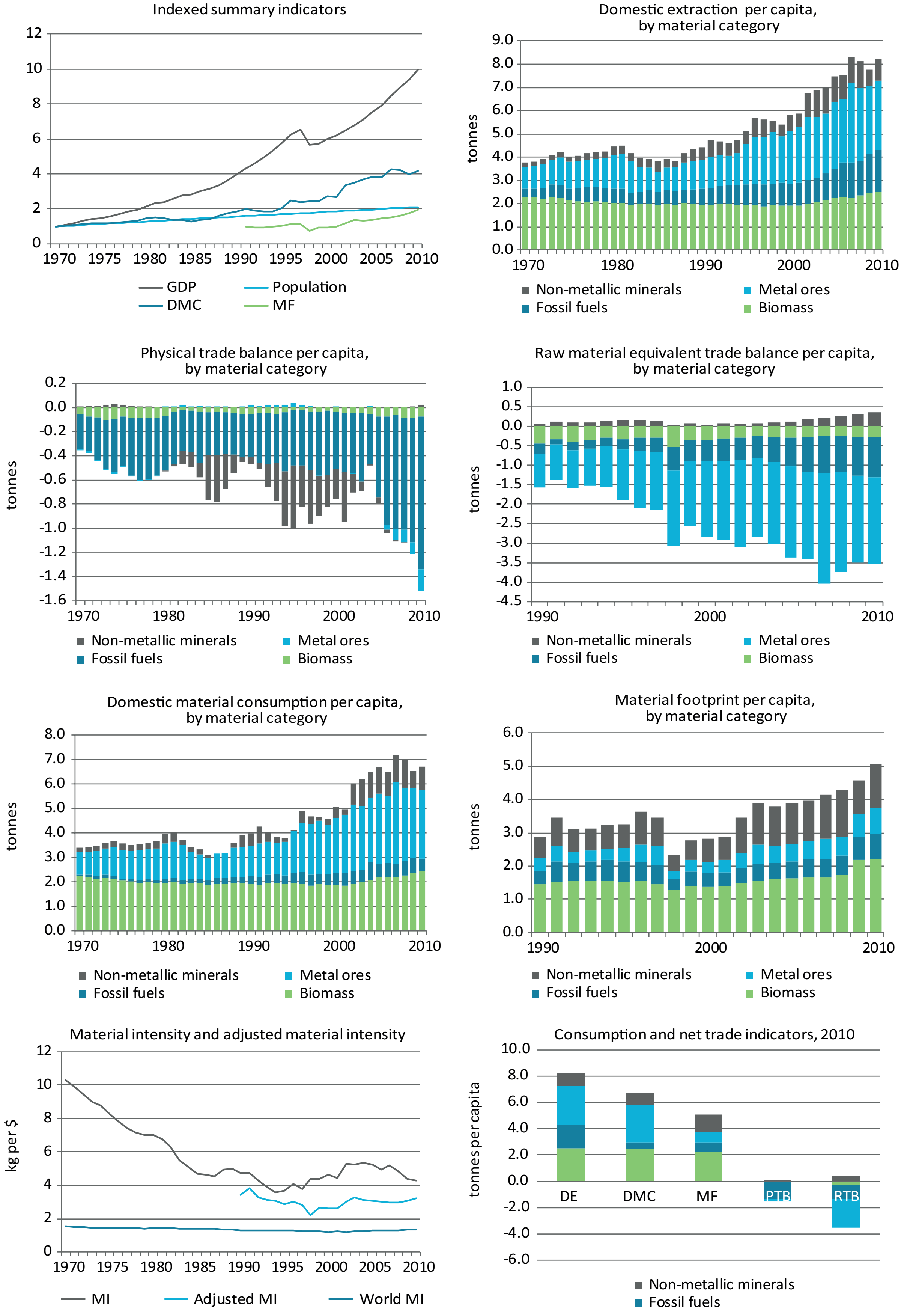
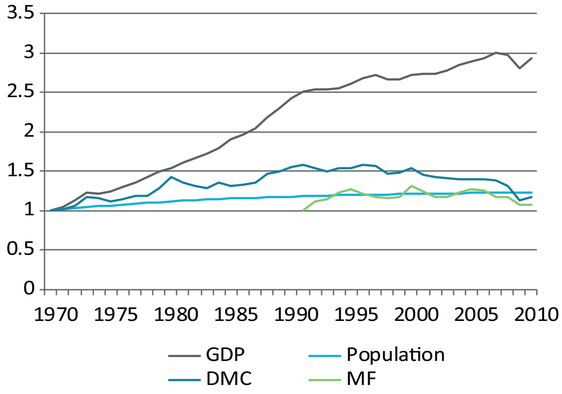
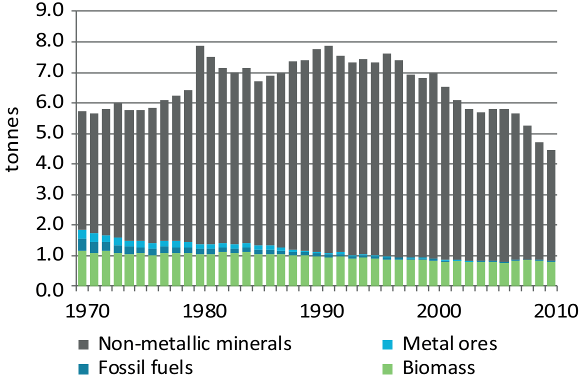


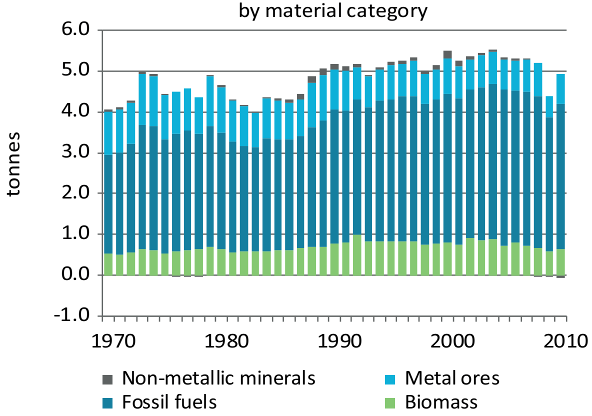
Figure 65. Indonesia

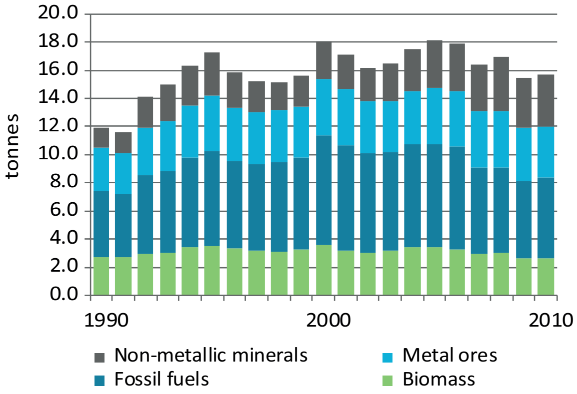
JAPAN

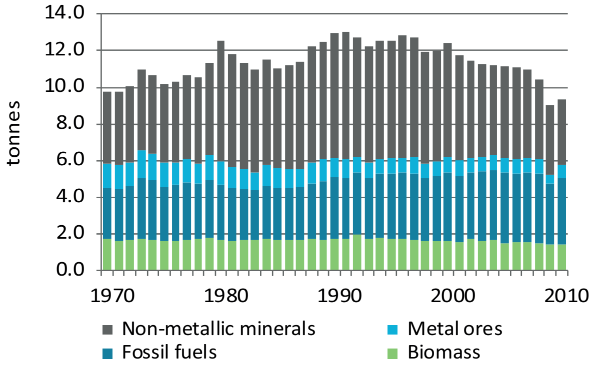
The indexed summary indicators for Japan show a strong growth in affluence from 1970 to 1990 (GDP > population) followed by much slower growth from 1990 on, reflecting Japan's "lost two decades". Improvements in material productivity appear to have been ongoing for the whole 1970 to 2010 period (GDP > DMC), driven for the first two decades by the rapid increases in GDP, and over the latter two decades by a decline in total DMC. Importantly, simultaneous growth in GDP and contraction in DMC indicates a relatively rare example of two decades of absolute (as opposed to relative) decoupling, on these metrics. Looking at MF however, we see marginal growth from 1990 to 2010, so once embodied raw materials are taken into account, we no longer appear to have absolute decoupling. The extremely large differences we see between DE, DMC and MF for Japan are also interesting. Comparing DE to DMC we see that Japan is only ever met a significant portion of its domestic requirements for non-metallic minerals, and to a lesser extent biomass, from DE. The reliance on imported biomass is almost certainly greater than it appears due to concentration prior to trade. This heavy dependence on net imports of primary materials is magnified greatly when we take embodied materials into account in MF. Where Japan has DMC 30 to 50% lower than the VHDI group averages we saw in Chapter 4, its MF levels are close to VHDI average for the full period. An interesting comparison can be made between consumption and net trade indicators for Japan and the US, the world's two largest VDHI group economies. Where there is a stark difference in 2010 between per capita DE and DMC for the two countries, with Japan's level around one quarter and one half US levels, on the MF metric Japan uses around three quarters the US requirement, and obtains almost twice as much per capita from the rest of the world, using the RTB metric.

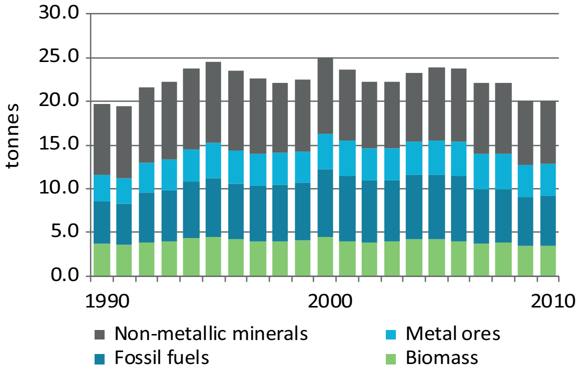

Indexed summary indicators

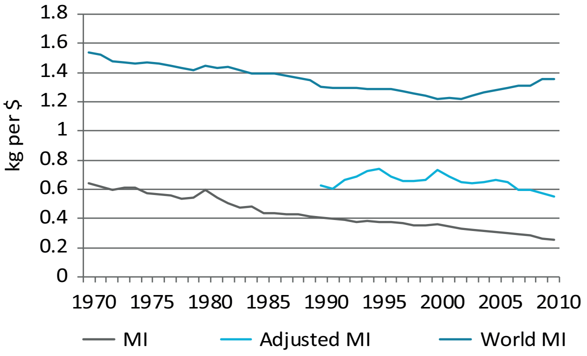

Domestic extraction per capita, by material category


Physical trade balance per capita, by material category


Raw material equivalent trade balance per capita, by material category


Domestic material consumption per capita, by material category


Material footprint per capita, by material category


Material intensity and adjusted material intensity

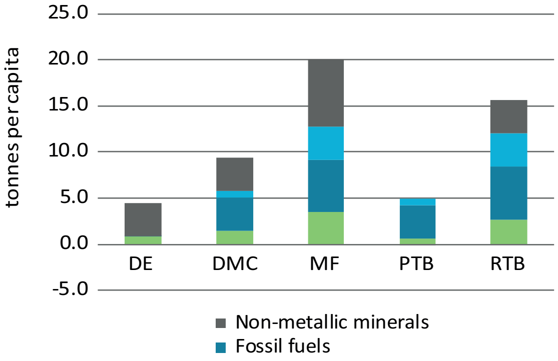

Consumption and net trade indicators, 2010

Figure 66. Japan

MEXICO

Mexico shows a very tight coupling of GDP and DMC after a brief period of relative decoupling from 1970 to 1980. Population growth has been high compared to its HHDI group, and GDP growth low, so affluence increased by only 70% over the full four decades, which is poor for its group. DE shows very rapid growth in fossil fuels between the early 1970s and early 1980s, which reflects the growth of Mexico as a significant petroleum producing country in response to oil supply and price shocks of the 1970s. Other mineral material categories grow at a much slower and steadier pace over the full period, while biomass remains largely static in per capita terms. PTB shows that when DE per capita of fossil fuels peaked, in 1983, almost exactly 50% of it was accounted for by net exports, a proportion which has declined over time so that by 2010 net exports were only 5% of DE, with a trend that indicated Mexico was likely to be a net importer of fossil fuels shortly thereafter. Mexico's dependence on net imports of biomass and metals grew from roughly the same time its fossil fuel exports peaked. In contrast to PTB, RTB shows that the fossil fuels embodied in Mexico's exports actually higher in 2010 than 1990, although at a level only 67% that of their peak in 1995. MI has been largely static over time, while adjusted MI has declined approximately 15% over the last two decades. DMC and MF per capita in 2010 differed only marginally in both total volumes, and in the relative shares of different materials.

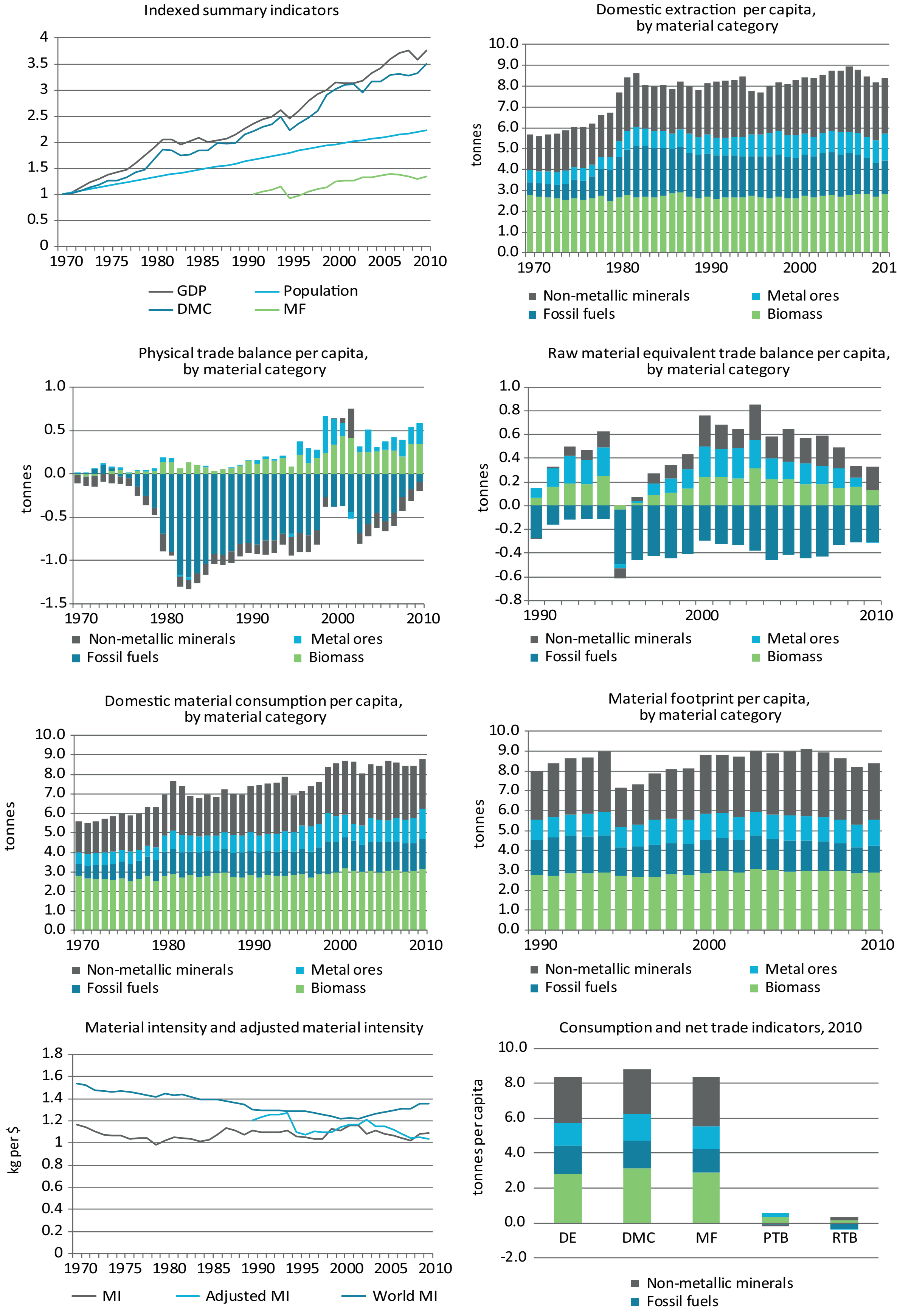


Figure 67. Mexico

NIGERIA

Nigeria's population growth has been so rapid that, despite the near tripling of DMC over the period, the average inhabitant used as little in the way of primary resources at the end of the period as at the beginning. While GDP grew over four fold, this only translated into an increase in affluence of 41%. The pattern of high population growth cancelling out increases in DMC that might have been attained on a per capita basis, and greatly slowing growth in affluence, matches the pattern for the LHDI group, to which Nigeria belongs. This pattern contrasts strongly with the gains in affluence and increased per capita availability of resources seen for the MHDI group, as typified by India and Indonesia. Despite considerable DE of fossil fuels, after physical trade is taken into account we see a pattern of mineral resources reducing their share of DMC, which suggests Nigeria's socio-metabolic transition is stalled or perhaps regressing. RTB indicates that Nigeria's material standard of living is in fact even lower than its low DMC per capita, with a similar stagnation in any industrial transition. MI increased until the mid-1990s, but then began to improve (decrease) strongly from that point, an improvement also seen in adjusted MI. In 2010, the net exports of fossil fuels on either PTB or RTB measures account for > 80% of Nigeria's DE of fossil fuels.

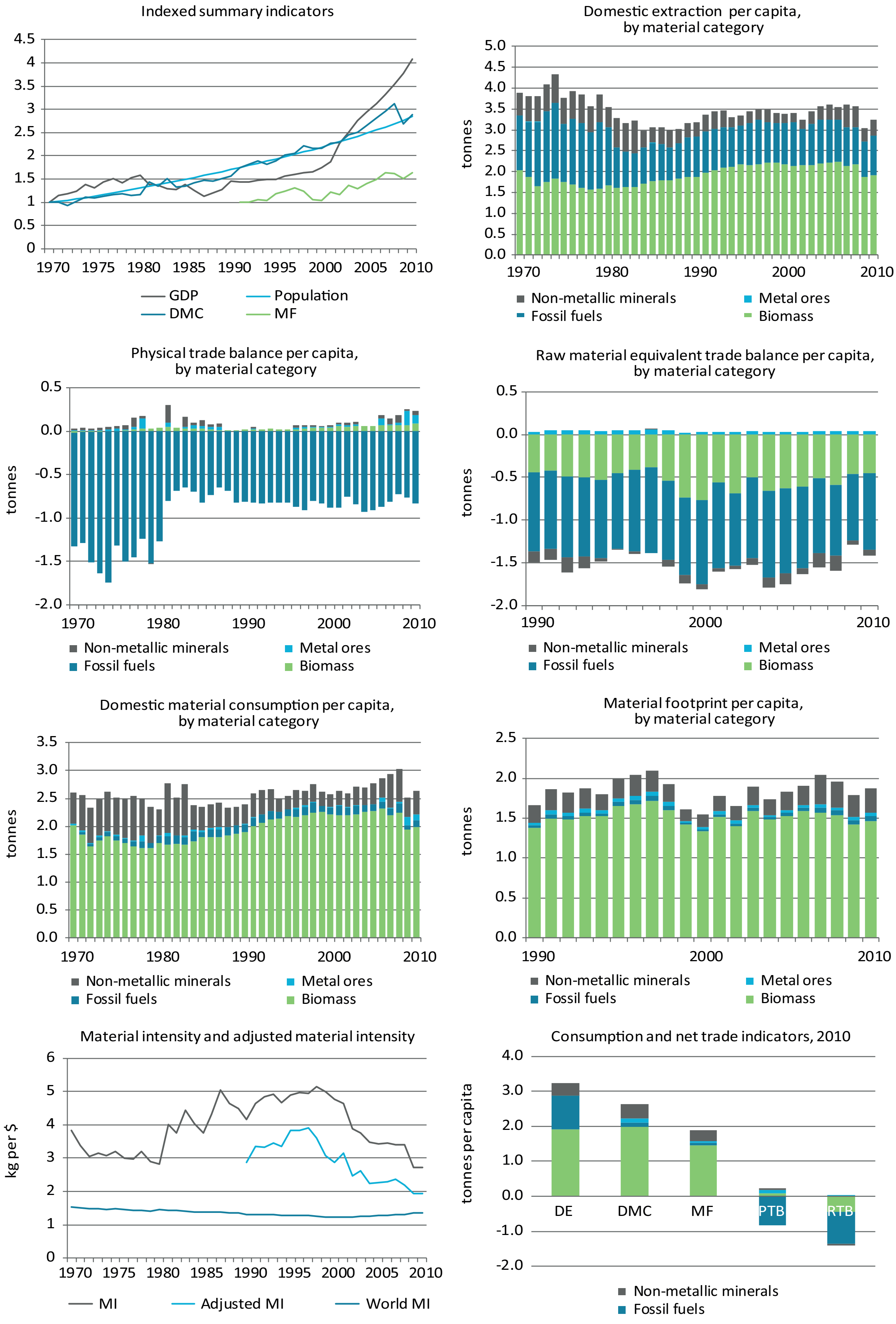


Figure 68. Nigeria

PAKISTAN

The indexed summary indicators for Pakistan show some relative decoupling of GDP and DMC. Population growth was considerably above average for the MHDI group, while GDP growth was only average, yielding an improvement in affluence below average for its group. DE indicates a slow but consistent growth in the share of mineral resource inputs compared to biomass, which indicates ongoing industrialization. PTB shows a period of steadily growing net imports until the mid to late-1990s, from which point growth has been minimal. PTB has been dominated by imports of fossil fuels, but these remain small in per capita terms (never exceeding 0.2 tonnes per capita), with Pakistan meeting 55% of its fossil fuel requirements DE. RTB is dominated by net exports of embodied biomass, and also indicates that Pakistan is a minor net exporter of fossil fuels on this measure, as well as of non-metallic minerals. MI improved consistently for the full period, and this was also reflected in adjusted MI. Pakistan's low DMC per capita of less than four tonnes per capita still overstated consumption by 40% compared to MF.

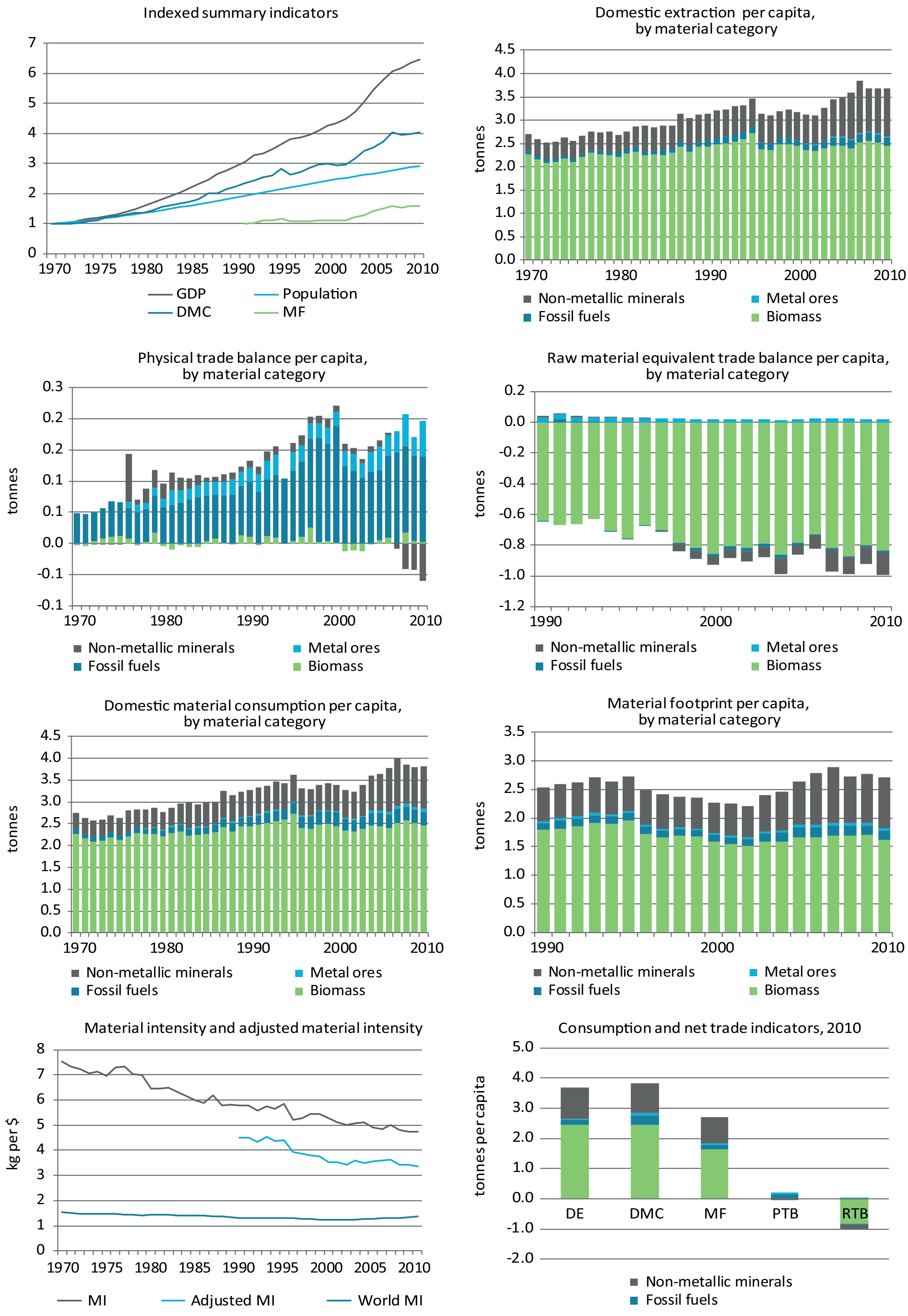


Figure 69. Pakistan

POLAND

In Poland there are two very distinct periods with regard to decoupling, with GDP and DMC closely coupled until the dissolution of the Eastern Bloc at the beginning of the 1990s, at which point a regime of strong relative decoupling replaced it. Population also declined slightly from the mid-1990sresuming very slow growth from 2007, accentuating the accelerated increase in affluence which took place period 1991 to 2010 (112%) compared to the period 1970 to 1990 (23%). DE and PTB show that accelerated increase in affluence coincided with a period where Poland reduced its DE of fossil fuels and became a net importer of them. Poland also became a minor exporter of biomass, despite a small contraction in DE in this category. RTB indicates that when embodiment is taken into account, Poland was a major net exporter off all categories in 1990, however the level of these exports decreased rapidly, and net imports of (embodied) metal ores commenced from 1996. With the exception of non-metallic minerals, Poland's DMC per capita in all categories has been quite stable since the mid-1990s. MI declines rapidly from the late 1980s, however the decline in adjusted MI is much slower until the two measures roughly converge for the new millennium, and then continue on near parallel trajectories from that point.

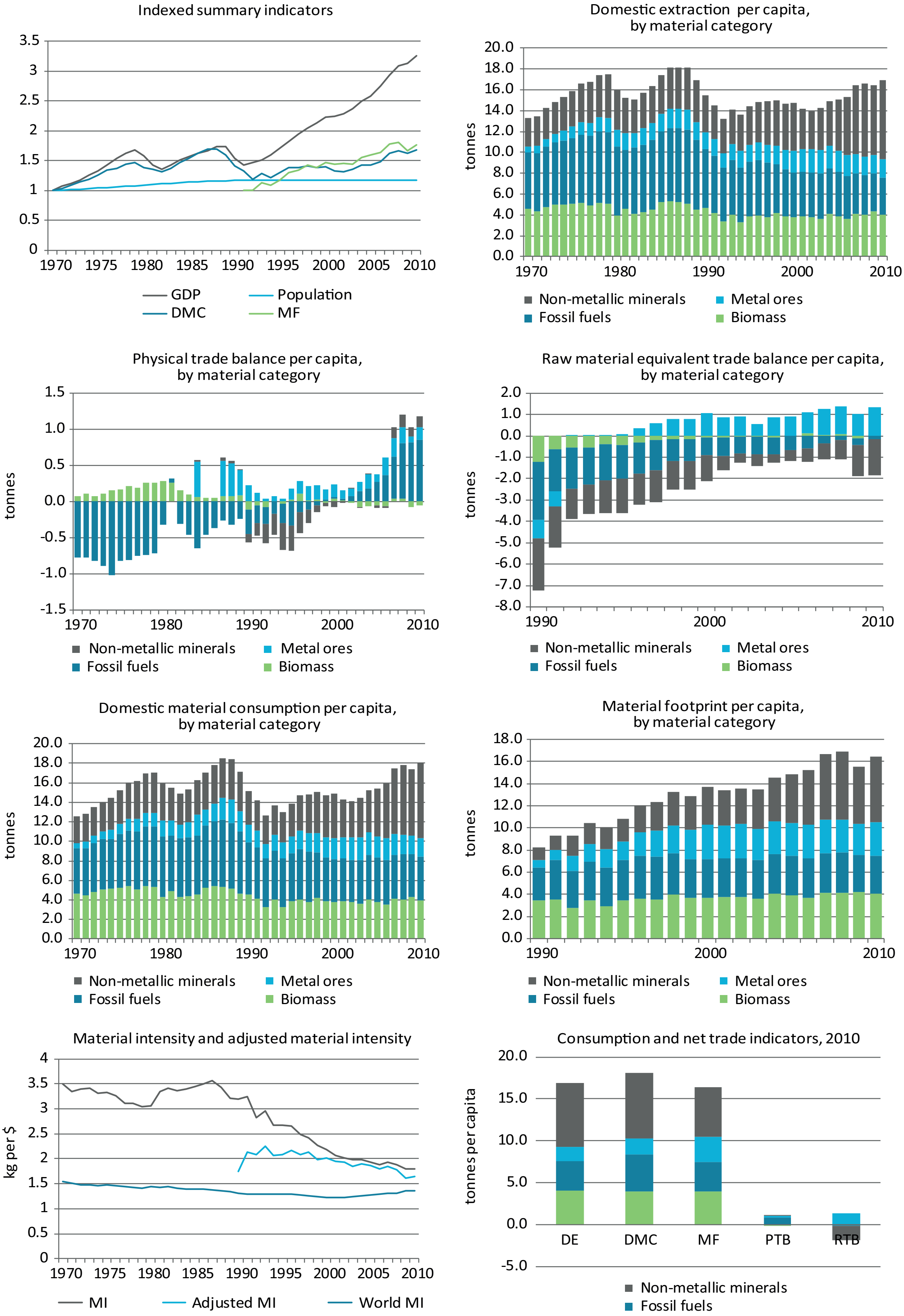
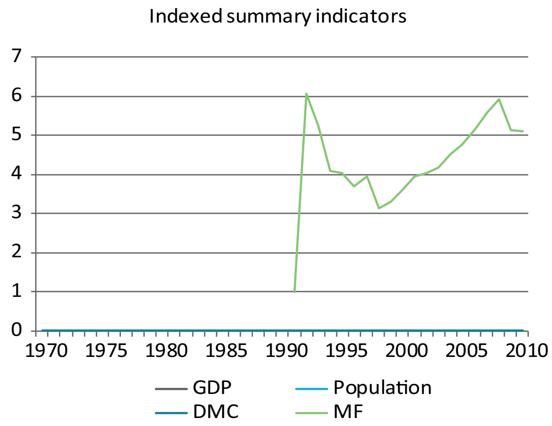
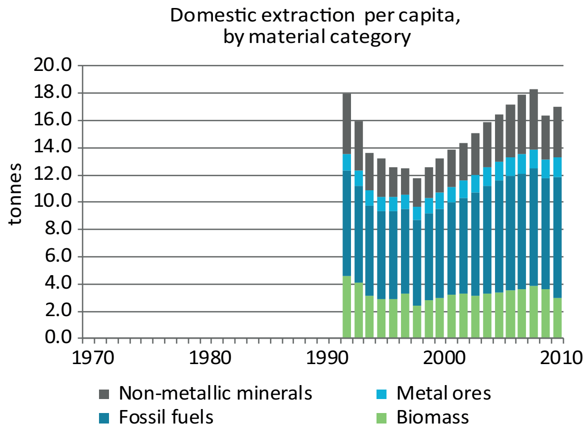


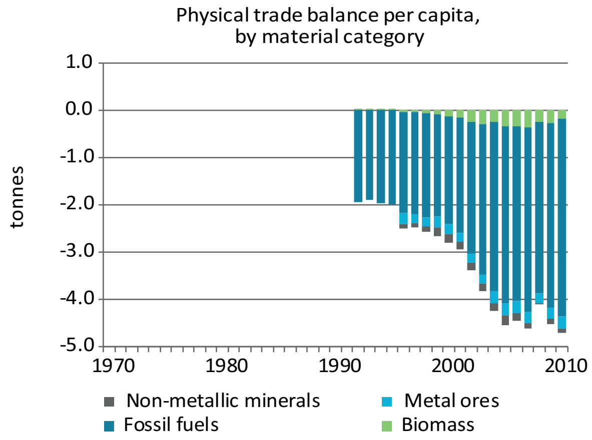
Figure 70. Poland

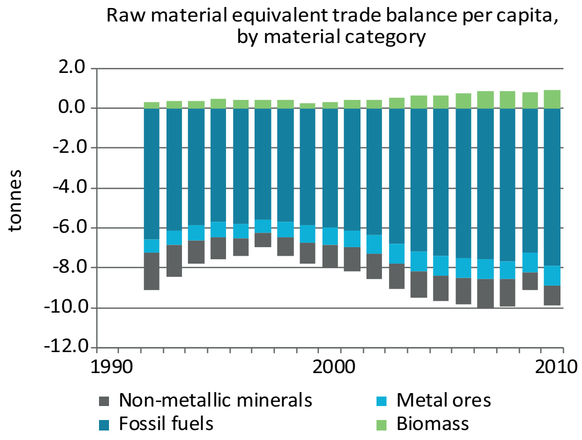
RUSSIAN FEDERATION

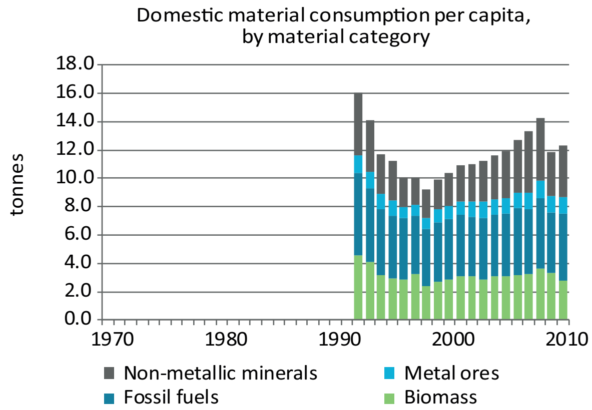
For the Russian Federation, data for the indexed summary indicators show a rapid and large decline in GDP, DMC, and MF from the outset, when it came into being as an independent successor state to the USSR. This reflects the enormous economic dislocation that accompanied the rapid transition from being the core of a larger, centrally planned economy to being and independent state with trade oriented towards the wider global economy. Unusually, even population declined. DMC and MF fell much faster than GDP, indicating rapid increases in material productivity during this period. DE reflects the same precipitate fall through to 1998, with DE of non-metallic minerals falling by 53%, and fossil fuels by 20%, however PTB shows net exports of fossil fuels never fell significantly, and grew continuously from 1993, suggesting that the sectors pre-existing orientation to external markets protected it. In contrast, net exports on the RTB metric, including fossil fuels, did reflect a marked decline over the main contraction period. This probably reflects contraction of industries which had been exporting, but which had previously relied on inputs of materials and energy at lower than market prices. It is noteworthy that the embodiment of fossil fuels in RTB in 1998, at the height of the contraction, accounted for 92% of DE of fossil fuels, and even by 2010, the corresponding figure was still 88%. The corresponding figures for metal ores were 76% (1998) and 66% (2010).This gives an indication of how dependent the Russian export sector is on high inputs of materials and energy. MI decreased strongly, while adjusted MI also decreased, but more slowly, especially over the last decade. MF in 2010 was only 65% of DMC.

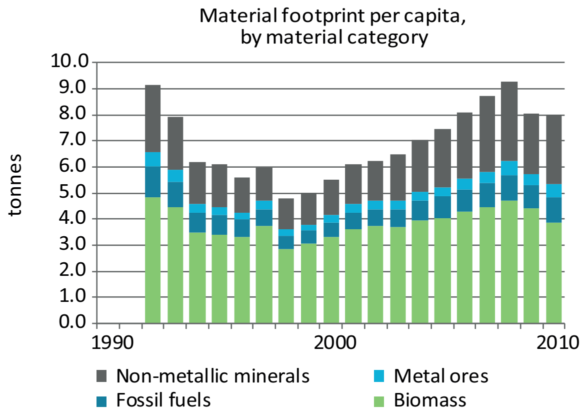


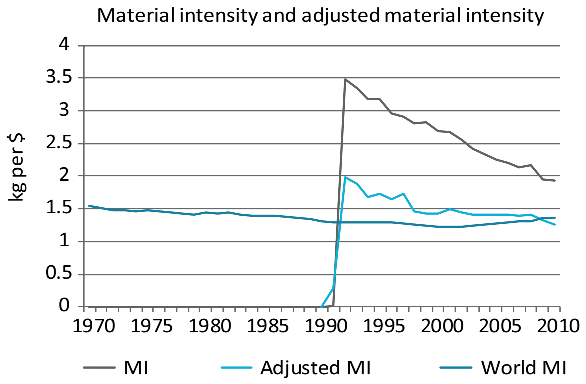












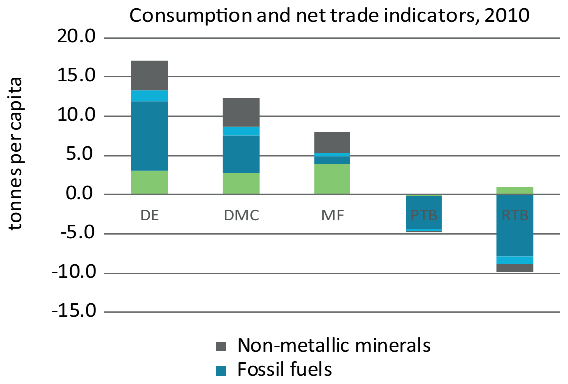


Figure 71. Russian Federation

SAUDI ARABIA

Saudi Arabia's indexed summary indicators show very strong growth in GDP, almost twice as fast as the VHDI group average, but also extraordinarily rapid growth in population. This combination yielded a growth in affluence over the full period below 100%, a low result for a VHDI country. DMC increased over 11 fold, almost twice the rate of GDP, which translated into a long-term decline in material productivity. DE per capita is dominated by fossil fuels, and peaked in the 1970s. It then declined rapidly from the early 1980s to a low point in the mid-1980s coincident with the oil glut and low oil prices of that time. This reflects Saudi Arabia's dominant role within the OPEC oil cartel and its ability to rapidly increase or decrease oil production in response to market conditions. The dominance of fossil fuels in Saudi Arabia's PTB is even more complete. RTB reflects a large embodiment of construction minerals in addition to fossil fuels, which may reflect the infrastructure required to extract (and refine a portion of) huge volumes of petroleum products. RTB also shows a large quantity of biomass embodied in Saudi Arabia's imports, a manifestation of indirectly trading petroleum for food. The trend of rapidly increasing MI is not really reflected in adjusted MI, indicating relatively static rather than deteriorating material productivity after allowing for embodied materials.

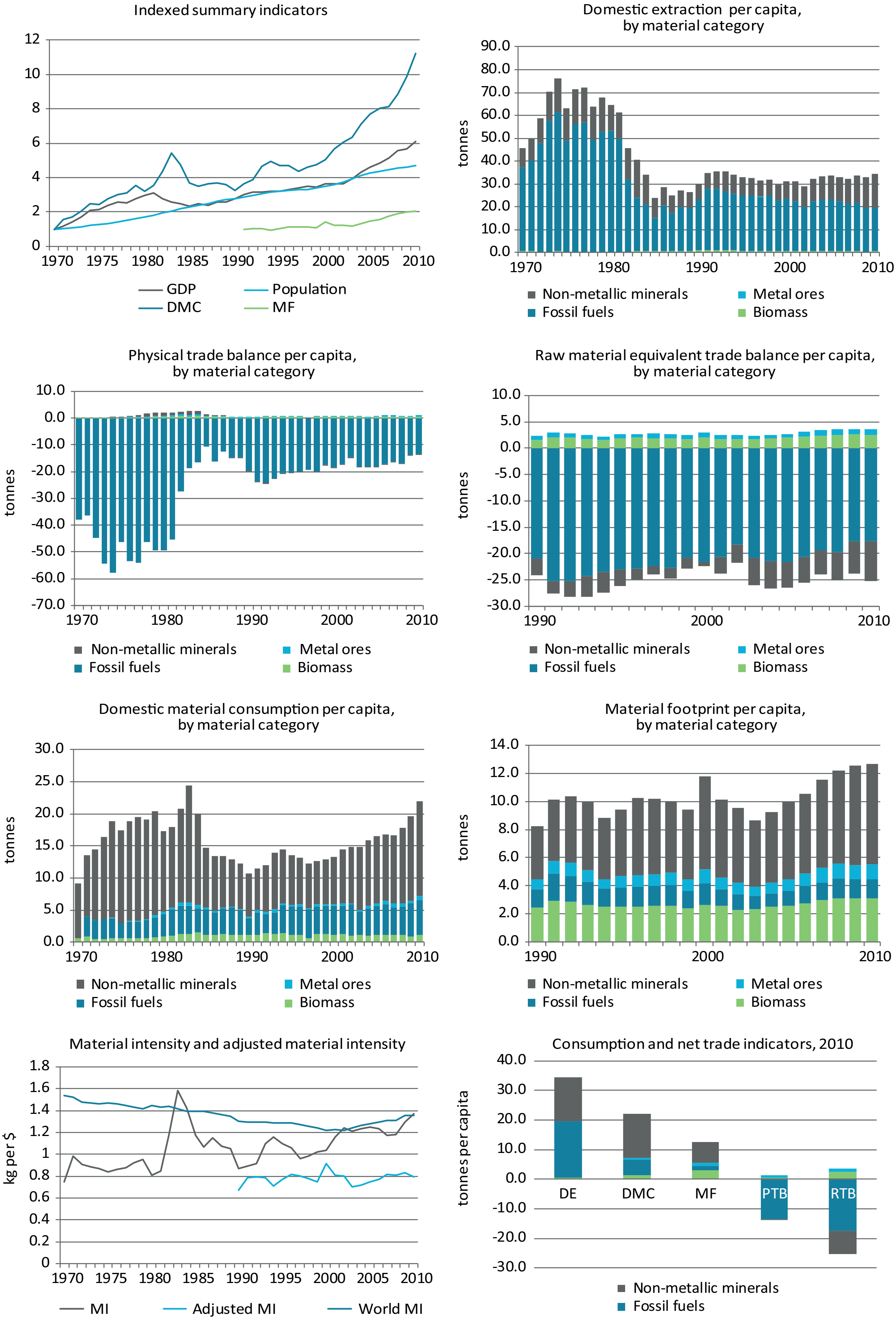
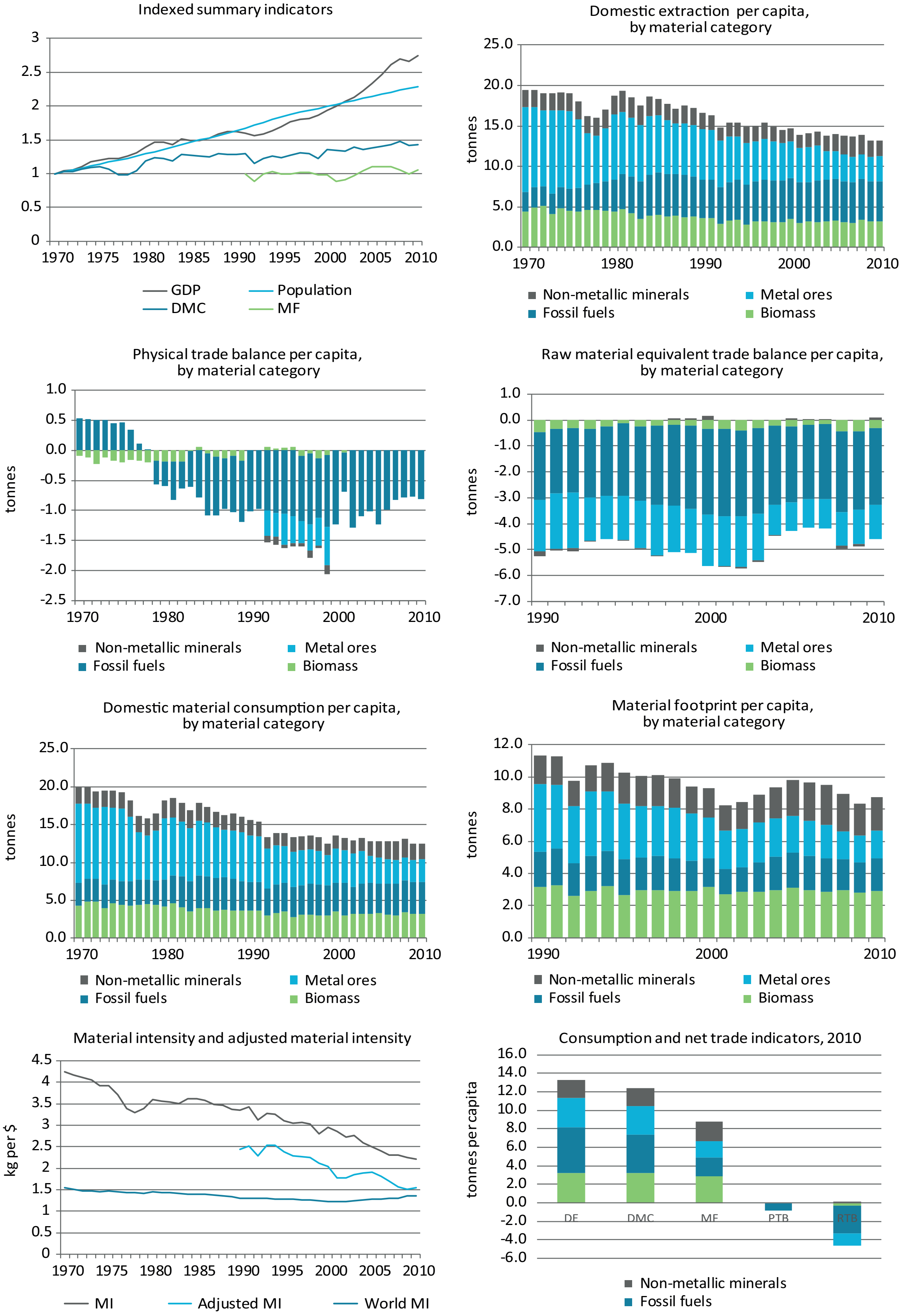


Figure 72. Saudi Arabia

SOUTH AFRICA

The indexed summary indicators for South Africa show relative decoupling of GDP and DMC for virtually the entire period, such that material productivity roughly doubled. Population growth was around average for the MHDI group, but GDP growth less than half the group average, yielding virtually no improvements in affluence until the period after 2002. DE shows a society with a high minerals component compared to biomass, and this is also reflected in DMC, indicating a nation which has industrialized to a considerable extent. Metal ores dominate in 1970, but by the mid-1990s fossil fuels come to dominate. The high levels of both DE and DMC of metal ores can be in large part explained by South Africa's large gold sector, where concentration of ore as extracted prior to trade (as gold metal) is so high that effectively all of the ore is allocated to the domestic DMC account, even though nearly all of the gold is exported. The total minerals component has decreased slightly since 1970, while total DE and DMC per capita have both declined strongly, by 32% and 38% respectively. PTB shows a transition from fossil fuel importer to exporter by 1980. RTB shows South Africa as a net exporter of embodied materials in all categories except, occasionally, non-metallic minerals. Both MI and adjusted MI have decreased consistently. In 2010, MF indicates final consumption of 8.7 tonnes per capita, which is only 70% of the 12.4 tonnes indicated by DMC. RTB for the same year is over 450% higher than PTB.


Indexed summary indicators

Domestic extraction per capita, by material category

Physical trade balance per capita, by material category

Raw material equivalent trade balance per capita, by material category

Domestic material consumption per capita, by material category

Material footprint per capita, by material category

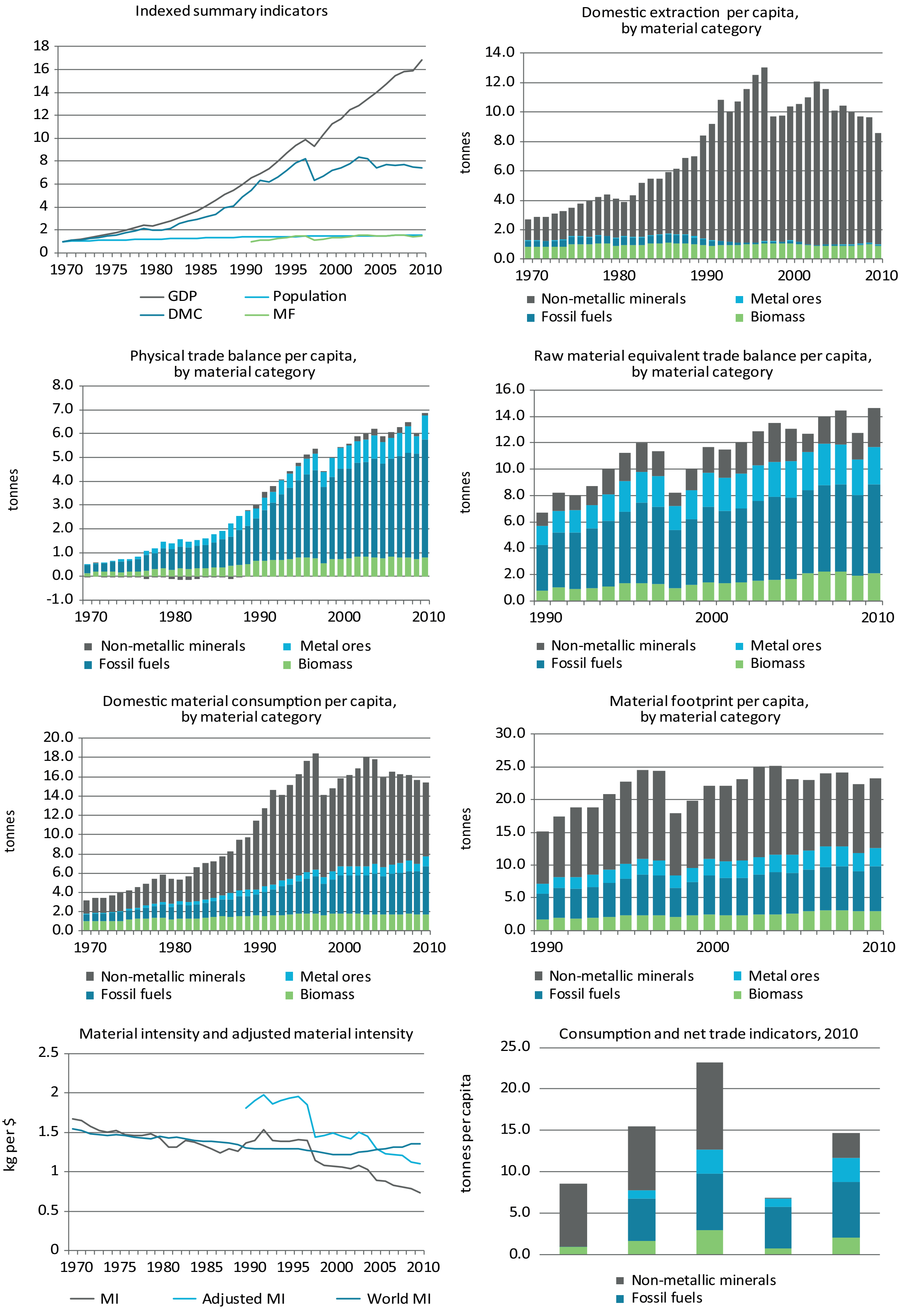
Material intensity and adjusted material intensity

Consumption and net trade indicators, 2010

Figure 73. South Africa

SOUTH KOREA

The most conspicuous feature of the indexed summary indicators for South Korea is the abrupt stabilization of DMC in the wake of the Asian financial crisis in 1997, after two and a half decades of very rapid growth. GDP, after a one year contraction, resumed growing at a very rapid pace, over which effectively divides South Korea's record into two distinct periods with regard to decoupling, an early period where economic growth was almost directly coupled to increased materials use, then a later period of very strong relative and weak absolute decoupling. With population growing slowly, both affluence grew rapidly across almost the entire period. DE is almost entirely composed of non-metallic minerals, which has been over 10 tonnes per capita in some years and reflects a very strong construction sector. The DE profile combined with PTB shows Korea to be almost totally dependent on imports for its fossil fuel and metals requirements, and also for around 45% of its biomass in 2010. While DMC per capita has stabilized, the share of fossil fuels has continued to grow (at a reduced pace) from 21% in 1997 to 33% in 2010. The share of metals also continued to grow, with growth in both categories coming at the expense of non-metallic minerals, which decreased from 65% to 50%. Very rapid decreases in MI from 1997 on are also reflected in adjusted MI. In 2010 MF was 50% higher than DMC, indicating a strong reliance on materials embodied in imports in addition to direct physical imports of materials. For the same year, both RTB and PTB South Korea was a net importer in all material categories, with RTB at almost 15 tonnes per capita, over twice the size of PTB.


Indexed summary indicators

Domestic extraction per capita, by material category

Physical trade balance per capita, by material category

Raw material equivalent trade balance per capita, by material category

Domestic material consumption per capita, by material category

Material footprint per capita, by material category

Material intensity and adjusted material intensity

Consumption and net trade indicators, 2010

Figure 74. South Korea

UNITED STATES

We can see from the indexed summary indicators that the United States experienced strong growth in affluence over the period 1970 to 2010, as indicated by the rapid growth of GDP compared to population. For most of the period improvements in material productivity (GDP/DMC) were much slower than affluence, as DMC grew at a rate intermediate between population and GDP, however the rapid drop in DMC in the wake of the GFC brought full period gains in material productivity back into line with increases in affluence. While DMC growth from 1970 to 2010 was around 50%, MF grew almost as much in half the time (1990 to 2010), indicating an increasing reliance on raw materials embodied in imported products. DE, DMC and MF profiles for the US very closely mirror the profile for the entire VHDI group discussed previously in Chapter 4, although the US profile is consistently higher by roughly 10 to 35%, with the largest differences in DE for the earlier years. The DE profile is interesting in that it declines slightly between 1970 and 2010 for the US whereas for the VHDI group it increases by over 15%. The general similarity between US and VHDI profiles is unsurprising due to the large contribution the US makes to the group total. The consumption and trade indicators show that by 2010, the US was reliant on net imports in physical terms (DE < DMC), and that it received and additional net inputs from embodiment of raw materials in trade (DMC < MF). Indeed, the largest net imports of primary materials came indirectly embodied rather than in direct physical form (PTB < RTB).

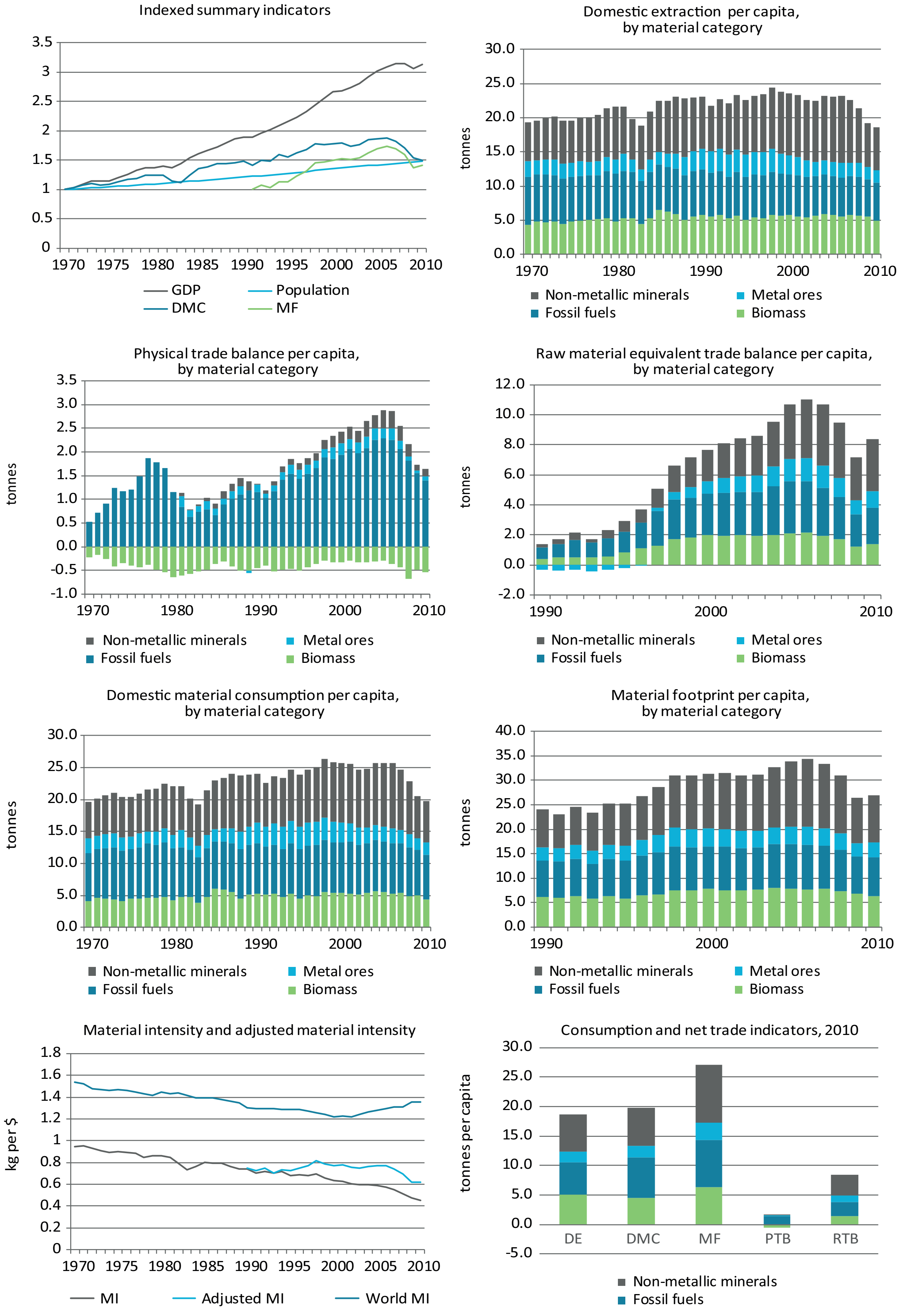
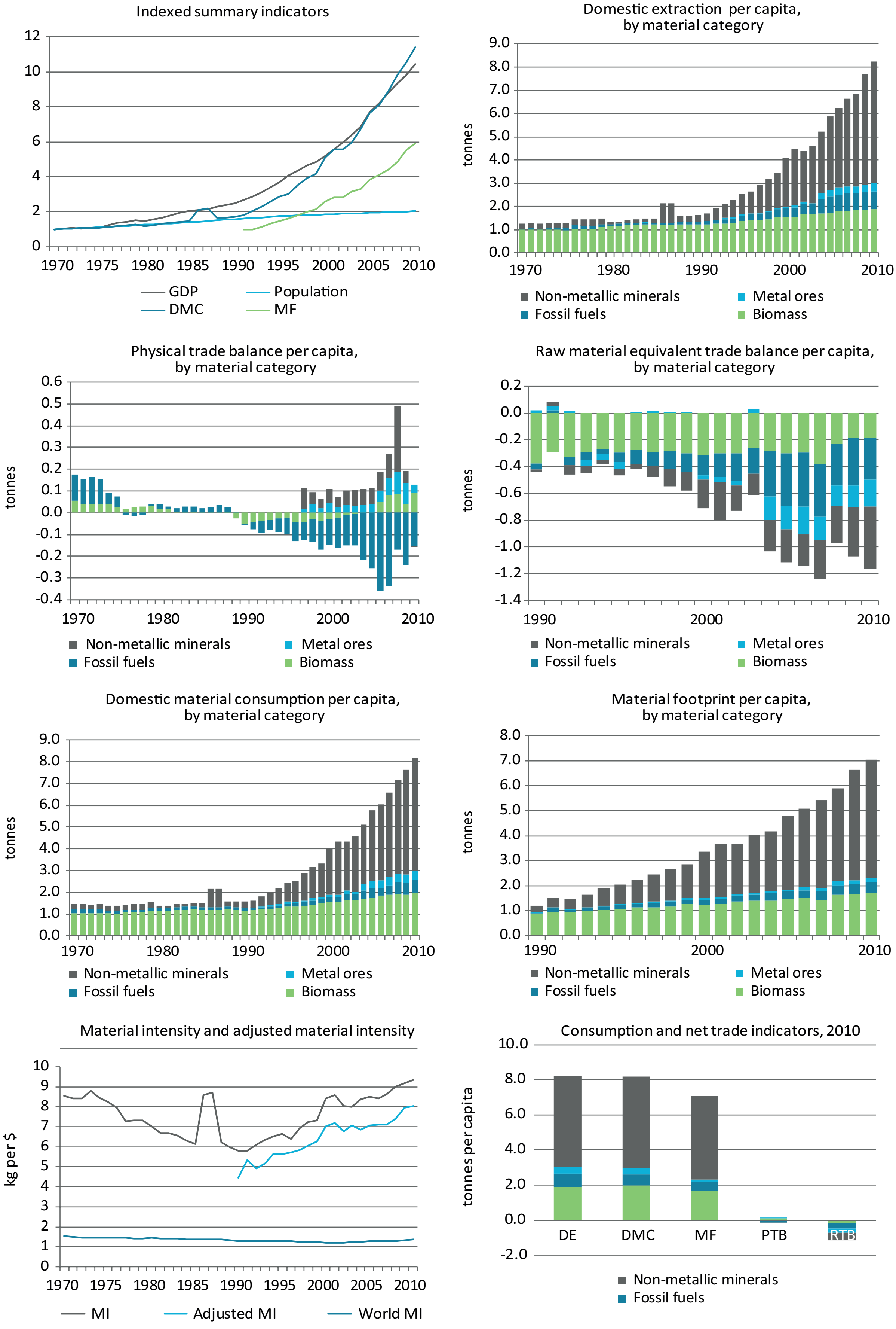


Figure 75. United States

VIET NAM

Viet Nam's indexed summary indicators show very close coupling between DMC and GDP, with DMC actually growing slightly faster than GDP. GDP which increased 68% more than the indexed average for the MHDI group, however DMC grew almost three times as fast as the MHDI average. Population growth was slightly less than the MHDI average, so Viet Nam's performance in increasing affluence was much stronger than the MHDI group overall. Prior to 1990 there was some relative decoupling, until the late 1980s, however this came to an end roughly contemporaneously with the spread of Doi Moi reforms. Both DE and DMC reflect a very rapid increase in the share of minerals compared to biomass, although all categories continued to grow in per capita terms. This indicates that Vietnam appears to be undergoing the transition to an industrialized society at an extraordinarily rapid pace. Despite very strong growth in fossil fuels and metal ores, it is non-metallic minerals which dominate both DE and DMC, indicating a very active construction sector, suggestive of a major infrastructure build-up. PTB shows Viet Nam making significant net exports of fossil fuels for a period beginning around 1990, which declined rapidly from their peak in 2006 due to rapidly increased domestic demand and static DE for fossil fuels. It was a physical net importer in all other categories for most of the new millennium. RTB shows Viet Nam as an increasing net exporter of embodied materials in all categories, although this trend appears to have changed with the onset of the GFC in 2008, especially with regard to biomass. MI decreased through to 1990 (although there was a brief spike up for the initial years of Doi Moi), but has been increasing rapidly ever since. This is also reflected in adjusted MI.


Indexed summary indicators

Domestic extraction per capita, by material category

Physical trade balance per capita, by material category

Raw material equivalent trade balance per capita, by material category

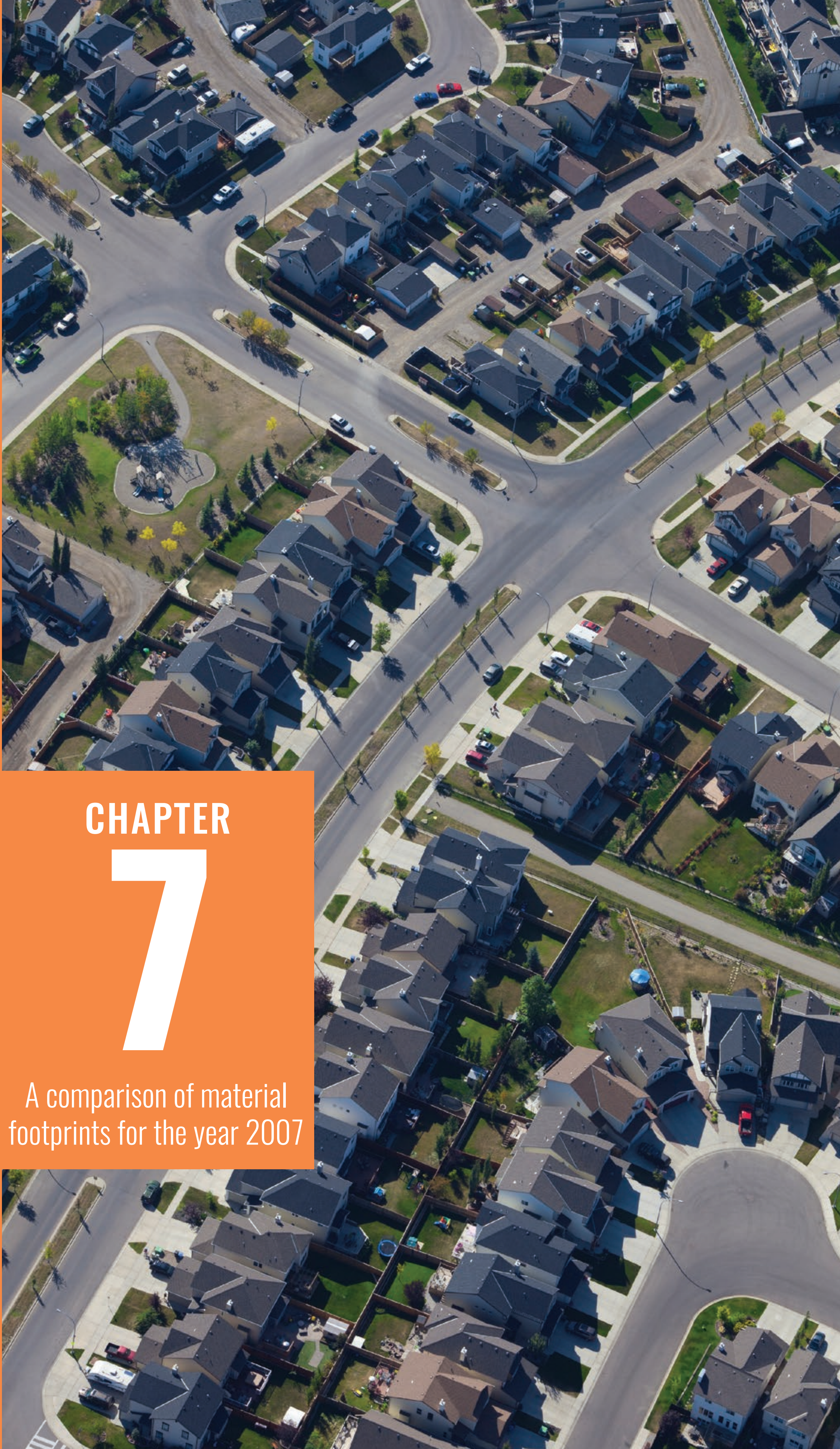
Domestic material consumption per capita, by material category

Material footprint per capita, by material category

Material intensity and adjusted material intensity

Consumption and net trade indicators, 2010

Figure 76. Viet Nam



CHAPTER

7

A comparison of material footprints for the year 2007

A comparison of material footprints for the year 2007

In Chapter 3 of this report we present material footprint accounts calculated with the Eora multi-regional global input-output (MRIO) database which is the most detailed multi-regional input-output framework that is currently available globally. Based on Eora we calculated time series covering the period from 1990 to 2010 in yearly time steps.

Accounting for material footprints is, however, a recent research activity, and requires further investigation into the robustness and reliability of the accounts to assess to what extent the choice of a particular MRIO framework determines the results. To this end we also calculated material footprints using two alternative MRIO frameworks, namely EXIOBASE and GTAP. Using EXIOBASE version 3.1, we calculated footprints for the years 2000, 2007 and 2010. GTAP version 8 provided an additional account for the year 2007 which we then compared to the results obtained through Eora.

Of the three databases we employed for the footprint analysis, Eora is the most detailed overall. It is different from EXIOBASE and GTAP in that sectoral detail varies among countries, from a minimum of 26 sectors up to 511 sectors, depending on the detail of national input-output tables that underpin the database. Like Eora, GTAP has a high level of regional detail specifying 129 countries and aggregated regions, but has a smaller number of sectors. EXIOBASE has a focus on Europe, with some additional detailed data for a number of large and important non-European economies. It has a greater level of sectoral detail than GTAP. While Eora uses all detail available in individual national input-output tables, the other two databases aggregate to a uniform level of sectoral detail for every country they report on. In this sense, Eora applies a different accounting strategy compared to both EXIOBASE and GTAP, in that it avoids ex-ante aggregation.

Table 7. Comparison of MRIO databases used in this report

	EORA	EXIOBASE 3.1	GTAP8
Time coverage	1990–2011	1995–2011	2007
Number of regions	187	49	129
Number of regions estimated	113	5	20
Number of sectors	26–511	160 (industries)	
200 (product groups)	57		
Transaction matrix dimension	14,760	5,676	7,353
Unit	US$	EUR	US$

The numbers for direct physical imports and exports, expressed as percentages of DMC and DE in Table 8, already provide some indication about the potential size of the material footprint of a country, and guidance as to whether MF is going to be lower or higher compared to DMC. Countries that have a very large share of their DMC sourced form imports, such as Japan or Korea, can be expected to have a material footprint considerably higher than their DMC. This is because the upstream material requirements of traded imported primary materials and final goods is typically large, due to both the concentration of commodities prior to trade, and via embodiment of materials and energy in products during the processing and manufacturing. This is also probably the case for some European economies for which the share of imports of DMC is around 30% or above. In contrast, countries which have a low share of imports of DMC (5%-10%) and a very high proportion of their DE related to exports (above 40%), such as Canada or Australia, would be expected to have a footprint which is quite a bit lower than their DMC. We would further expect that this should be consistently the case for all three footprint accounts, irrespective of which MRIO has been used to calculate the results.

Some exports such as copper, gold and meat have very large associated upstream material requirements, whereas crude oil, iron ore and wheat typically have much lower requirements (Schandl and West 2012).

Table 8. Share of imports of DMC and share of exports of DE, 2000, 2007 and 2010

	Imports/DMC		
	2000	2007	2010
AUS	6%	7%	8%
BRA	6%	6%	6%
CAN	22%	26%	33%
CHN	4%	6%	7%
DEU	31%	38%	39%
FRA	34%	41%	40%
GBR	30%	45%	47%
IDN	6%	5%	7%
IND	5%	6%	8%
ITA	38%	43%	50%
JPN	51%	59%	66%
KOR	48%	55%	65%
MEX	27%	15%	20%
POL	12%	18%	18%
RUS	6%	7%	7%
TUR	15%	20%	20%
USA	15%	16%	17%
ZAF	13%	17%	19%

	Exports/DE		
	2000	2007	2010
AUS	35%	42%	48%
BRA	15%	19%	18%
CAN	41%	46%	46%
CHN	3%	3%	2%
DEU	19%	28%	28%
FRA	23%	25%	27%
GBR	14%	20%	23%
IDN	18%	18%	24%
IND	2%	4%	5%
ITA	17%	21%	29%
JPN	12%	21%	28%
KOR	21%	27%	37%
MEX	22%	17%	16%
POL	11%	12%	12%
RUS	26%	32%	33%
TUR	5%	10%	11%
USA	7%	8%	12%
ZAF	20%	22%	24%

Figure 77 presents the material footprints for total final demand for 18 different countries for 2007 for all three MRIOs, and compares them to DMC.

For Korea, Japan, the US, Germany, the UK, France and Italy we find that the material footprint is larger than DMC for all three MRIOs demonstrating the fact that these economies are outsourcing part of their material intensive processes to other regions. Variation between the results from the three different MRIOs are small for each of these countries, showing a high level of agreement between the MRIOs, with the exception of Japan where EXIOBASE shows a much lower material footprint than the other two MRIOs.

As a general observation, in most cases Eora and GTAP are similar, with EXIOBASE deviating most from the other two. This is especially the case for China, where EXIOBASE calculates a much lower footprint than the other MRIOs. Australia's footprint is lower than its DMC for both Eora and GTAP – but not for EXIOBASE. Canada's footprint is larger than its DMC for all MRIOs, which could be explained by a combination of a high level of embodied materials in its imports, and/or the composition of its exports, suggesting exports characterized by relatively low levels of direct concentration prior to trade, and low indirect embodiment of materials.

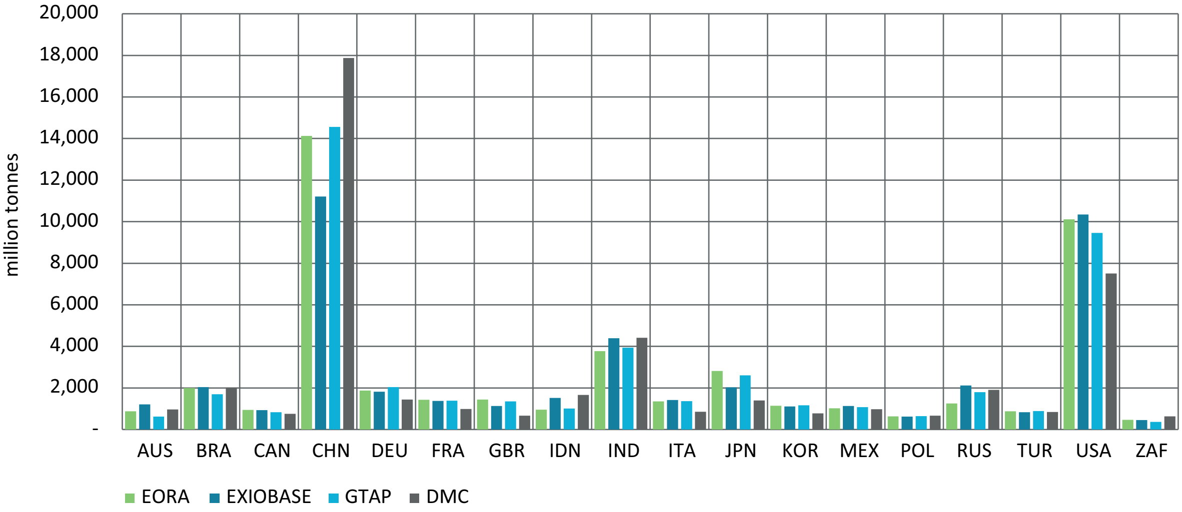


Figure 77. Material footprint for total final demand and DMC for 18 countries, year 2007

Differences in the material footprints between the three MRIOs is driven by their varying sectoral and geographical detail, and differences in the attribution of specific materials for direct imports and exports. I-O analysis starts from the assumption that a one homogeneous product is produced by each sector. The more aggregated sectors or regions are, the greater the degree to which the assumption of a homogeneous product will be violated, and the larger the attribution error will become. If a country has more trade in a domain where large upstream material requirements are expected, for example meat and dairy, then the attribution error will be larger as well.

The raw material equivalents (RME) of imports accounts for all upstream material flows, wherever they may have occurred, required to produce a nations imported products. For RME of exports we find good agreement between all three MRIOs for a small number of countries, including Brazil, Italy, Poland and the United States. The largest relative deviation among the three MRIOs for the RME of imports occurs for South Africa, China, and Canada (see Figure 78).

For RME of exports, largest differences between the results from the three different MRIOs are found for Japan, the United Kingdom, the United States, South Korea and France (see Figure 79).

Material footprint is attributed to different final demand categories. Here we distinguish final consumption of households and governments combined (Figure 80) from capital investment (Figure 81). Final consumption usually attracts a larger proportion of total footprint for most countries, but we see here that this is not the case for China. For China, Eora provides the highest estimate for final consumption of households and governments combined, at about 7 billion tonnes, which is more than double the amount EXIOBASE estimate. The GTAP result sits in between at around 5 billion tonnes. By way of contrast, GTAP calculates more than 9 billion tonnes of material footprint for capital investment in China, whereas Eora and EXIOBASE both estimate around 7 billion tonnes. It has been reported previously that China has curtailed consumption to allow for large investments in infrastructure, but it seems implausible that

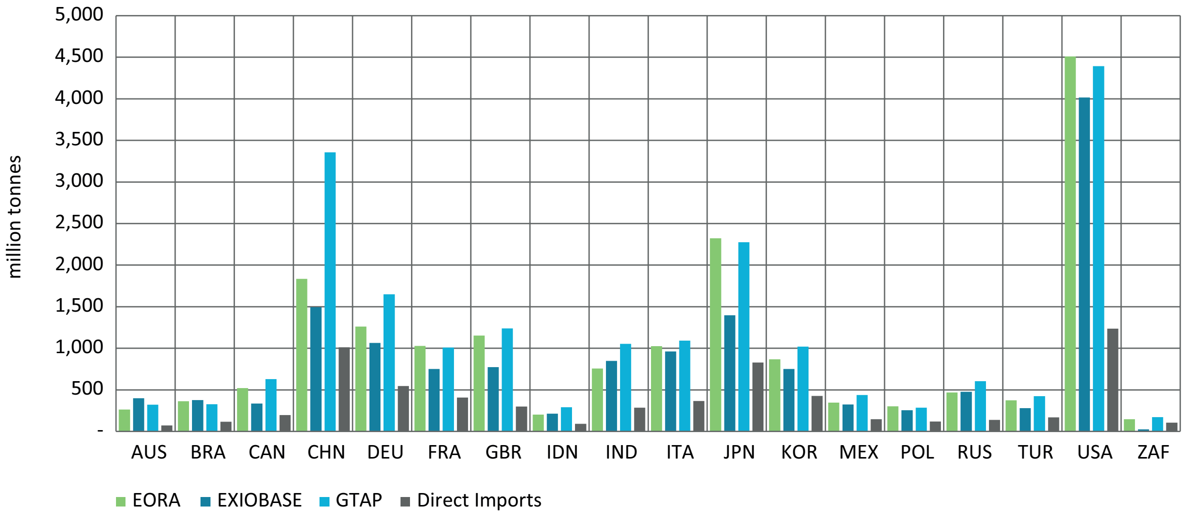


Figure 78. Raw material equivalents of imports for total final demand and direct imports for 18 countries, year 2007

China's consumption related footprints should total only 3 billion tonnes, as this less than 20% of its physically consumption (of almost 18 billion tonnes, as measured by DMC , see Figure 81). The higher estimates of between 5 and 7 billion tonnes seem more realistic. For many countries the three frameworks deliver more similar results than is the case for China, with Eora and GTAP estimates in most cases closer to each other than either is to EXIOBASE. Considerable differences also exist for Japan and the Russian Federation. Eora shows the highest footprint for consumption in Japan, GTAP for the Russian Federation.

For capital investment related material footprint EXIOBASE has higher results for Indonesia, India, the Russian Federation and the United States compared to the two other MRIO frameworks.

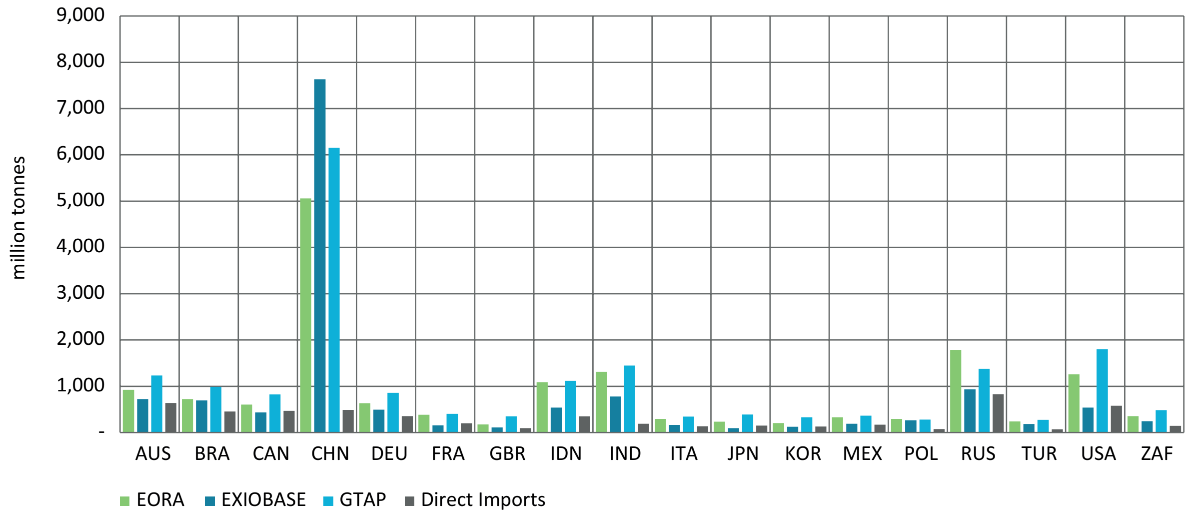


Figure 79. Raw material equivalents of exports for total final demand and direct imports for 18 countries, year 2007

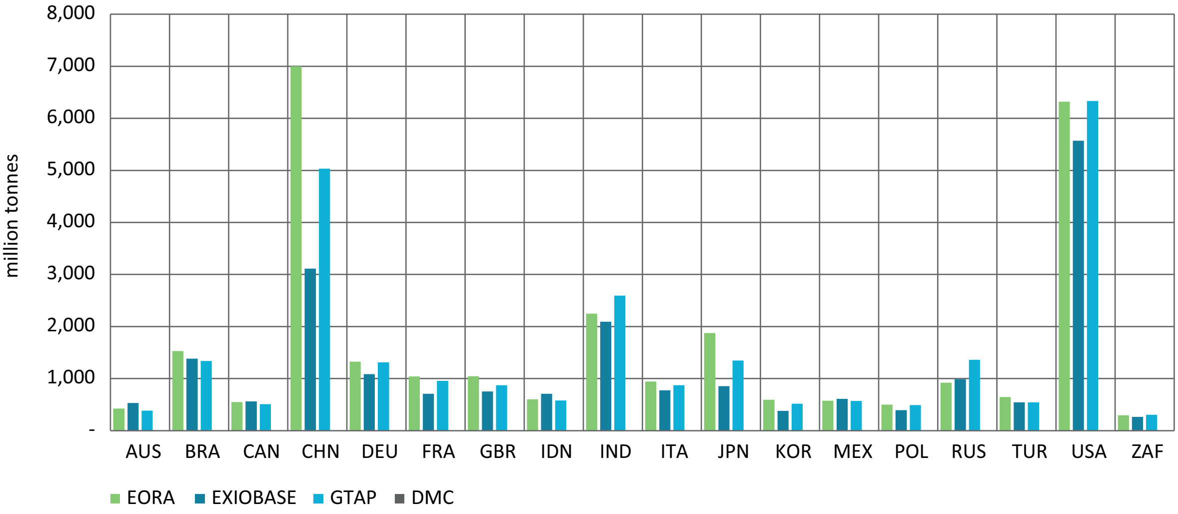


Figure 80. Material footprint final consumption of households and governments, year 2007

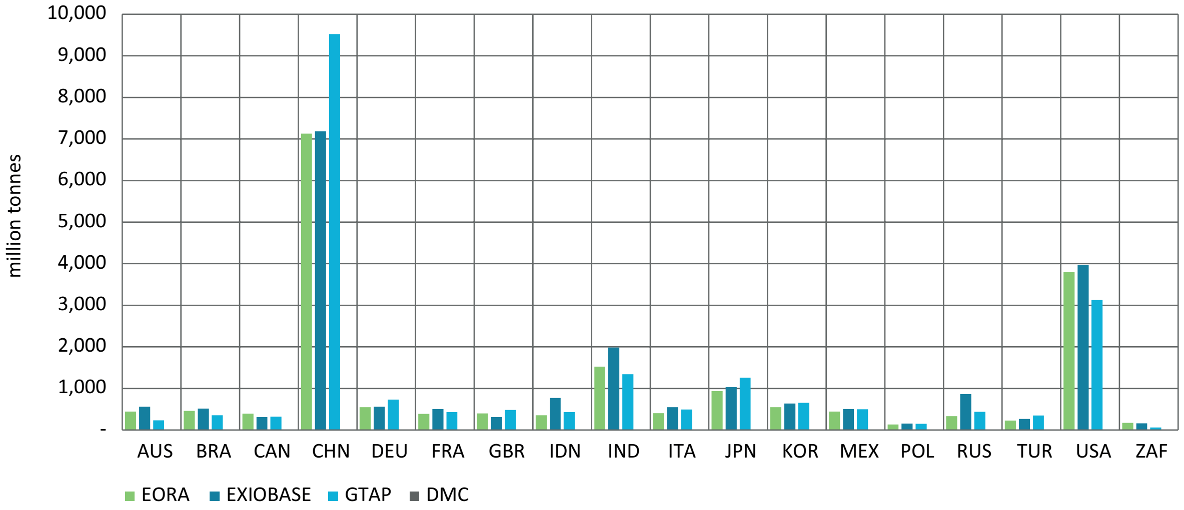


Figure 81. Material footprint of capital investment, year 2007

Sectoral material footprint results obtained for 6 broad economic sectors (see panel 1) helps to unpack why differences in total material footprint may have occurred.

The main reason for EXIOBASE showing a much higher MF for Australia than Eora and GTAP is the large attribution of material footprint to the manufacturing sector – double that of the two other MRIOs. This is also the case, to a lesser extent, for mining and energy, and construction. This large attribution to manufacturing is surprising considering the relatively small size of the manufacturing sector in Australia. EXIOBASE calculates a material footprint for Australia which is higher than Australia's DMC which is seems unrealistic, given that DMC for Australia is itself greatly inflated by the very high level of concentrated primary exports (especially of precious and base metals, and of animal products), which characterize the Australian economy.

For the main Asian manufacturers, China and Japan, GTAP shows a very high material footprint for the manufacturing sector, mirrored by a similarly high result calculated by Eora. EXIOBASE calculates a much lower manufacturing material footprint for these two countries. This is somewhat surprising given the importance of manufacturing in these countries. The largest contribution to material footprint in China stems, however, from the construction sector which is plausible when considering the large investment into urban and transport infrastructure that has been ongoing in China. All three MRIOs calculate a high result for the construction material footprint. Eora shows a much higher material footprint for agriculture, forestry and mining and energy sectors in China than the other two MRIOs. Overall, Eora and GTAP coincide in their total material footprint assessment for China which is about a quarter lower than China's DMC. Based on EXIOBASE, China's material footprint would only be 60% of its DMC. While no definite conclusion on which results are better can be made at this point, there is an intuitive reason to prefer the results from Eora and GTPA for China and Japan, as they seem to reflect the economic structure of the two countries better than EXIOBASE results do.

In summary, accounting for material footprints of consumption provides a different perspective on material use compared to the production based (territorial) accounts. Unlike the well-established indicator DMC, they account for the embodiment of all the upstream material requirements of imports and exports. The three MF accounts established through three different MRIOs are encouragingly similar for many countries at the aggregate level but show a lot of underlying discrepancy at a more disaggregated level for the different material groups and sectors.

In panels 2 to 4, the output for each of the three different MRIOs are regressed on each other by pairs, to test how closely they correlate, and to what degree they tend to over/under estimate relative to each other. The values used have been transformed to a per capita basis, to reduce the extremely large influence of China and US on results using raw MF. Pairs of graphs are shown side-by-side, with the left hand graph using all 18 countries, and the right hand graph showing results after both Australia and Canada are removed. These two countries were removed due to them being clear outliers (especially Australia).

For MF we see the strongest correlation between Eora and GTAP, for both the full and reduced country sets, with R2 above 0.9 in both cases. Removing Australia and Canada markedly reduces the degree to which GTAP underestimates relative to Eora, with the coefficient on x changing from 0.80 to 0.95. R2 is also high for both the full and reduced country sets in the Eora: EXIOBASE comparison, over 0.87 for both, however where EXIOBASE overestimates by around 12% relative to Eora using all countries, this changes to underestimating by around 13% for the reduced set. The lowest correlation for MF is between GTAP and EXIOBASE using the full country set, with R2 of 0.71, and GTAP estimating over 40% lower than EXIOBASE. The reduced set alters this relationship quite radically, improving R2 to 0.93, and also reducing the difference in the coefficient on x to just over 1%, the closest to a 1:1 relationship for any of the regressions.

For RME of imports, the closest agreement was again between Eora and GTAP, with R2 at 0.97 for both full and reduced country sets, and GTAP estimating only 5% to 7% higher than Eora. Comparing Eora and EXIOBASE, reducing the country set improved R2 considerably, from 0.82 to 0.94, but had little effect on the regression slope, with the coefficient on x indicating that EXIOBASE estimated 22% to 23% lower than Eora using either country set. The relationship between EXIOBASE and GTAP is very similar to that between EXIOBASE and Eora, with EXIOBASE estimating considerably lower than GTAP for both country sets. Given the strong correlation between GTAP and Eora for RME of imports, discussed previously, this is not surprising.

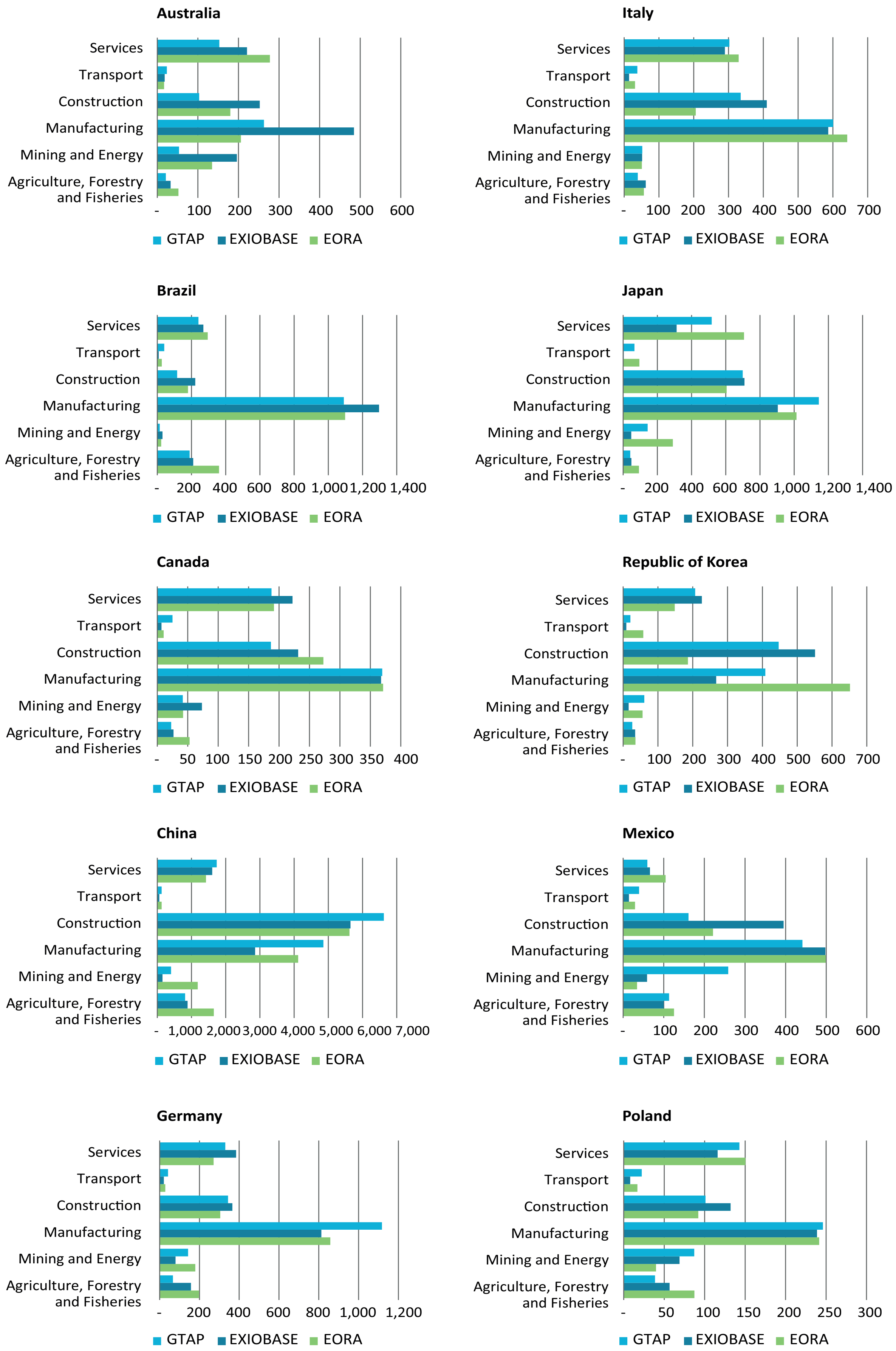
For RME of exports, the removal of Australia in particular can be seen to greatly reduce R2, which was over 0.97 in all regressions on the full country set, largely due to the huge leverage Australia exerted on these regressions. It also radically changes the coefficient on x in all three comparisons. After reducing the country set, the best correlation remained that between Eora and GTAP, with R2 at 0.73, and GTAP estimating lower, at 77% of Eora (this result is heavily influenced by Russia, without which the relationship would be much closer to 1:1). The worst correlation is between GTAP and EXIOBASE, with R2 of 0.54, however the coefficient on x of 0.91 indicates GTAP is only underestimating EXIOBASE by a relatively modest 9% on average.

Overall we see that Eora and GTAP results are more highly correlated with each other than either is with EXIOBASE. The correlation between Eora and GTAP is very strong for MF and RME of imports, regardless of whether the full or reduced country sets are used, however there is a much weaker correlation between the two for RME of exports, after the outliers of Australia and Canada are removed.

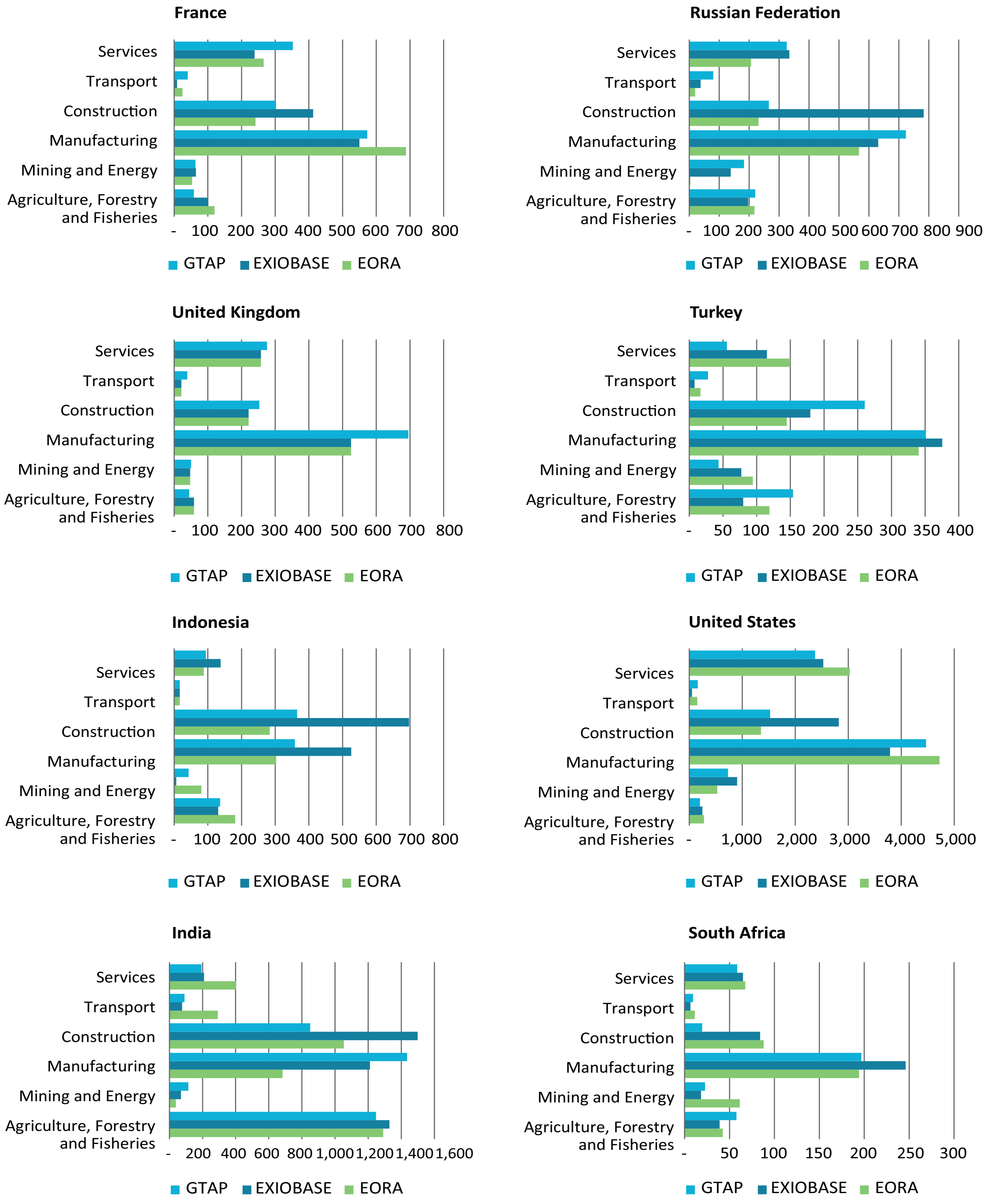
The relationship of MF to DMC is usually consistent in assigning whether a country's final demand is in large part dependent on primary materials from abroad, in which case MF is larger than DMC, or whether it extracts materials domestically for final consumption abroad, in which case where DMC is larger than MF. The EXIOBASE result for Australia does not follow this pattern, a result which is as yet unexplained.

It is difficult to judge which MRIO framework yields the "best" results, however as a general guideline, higher resolution of sectors and regions is better as it helps to reduce aggregation errors. This observation is in line with results of previous studies such as (Steen-Olsen et al. 2012), that compared the same group of MRIOs in the context of greenhouse gas emission multipliers. The approach adhered to in this report is thus to use accounts based on the Eora MRIO framework which offers the greatest resolution and longest time series data to date (Wiedmann et al. 2015b). Further analysis to identify the optimal level of aggregation of MRIOs will be necessary to judge the reliability of results. Ultimately there will be a need for harmonization of existing MRIO frameworks (Geschke et al. 2014) to create a global research infrastructure witch can be utilized by the global research, statistical and policy community. Such an infrastructure would need to be hosted, ideally, by an international organization such as the OECD or UNEP.

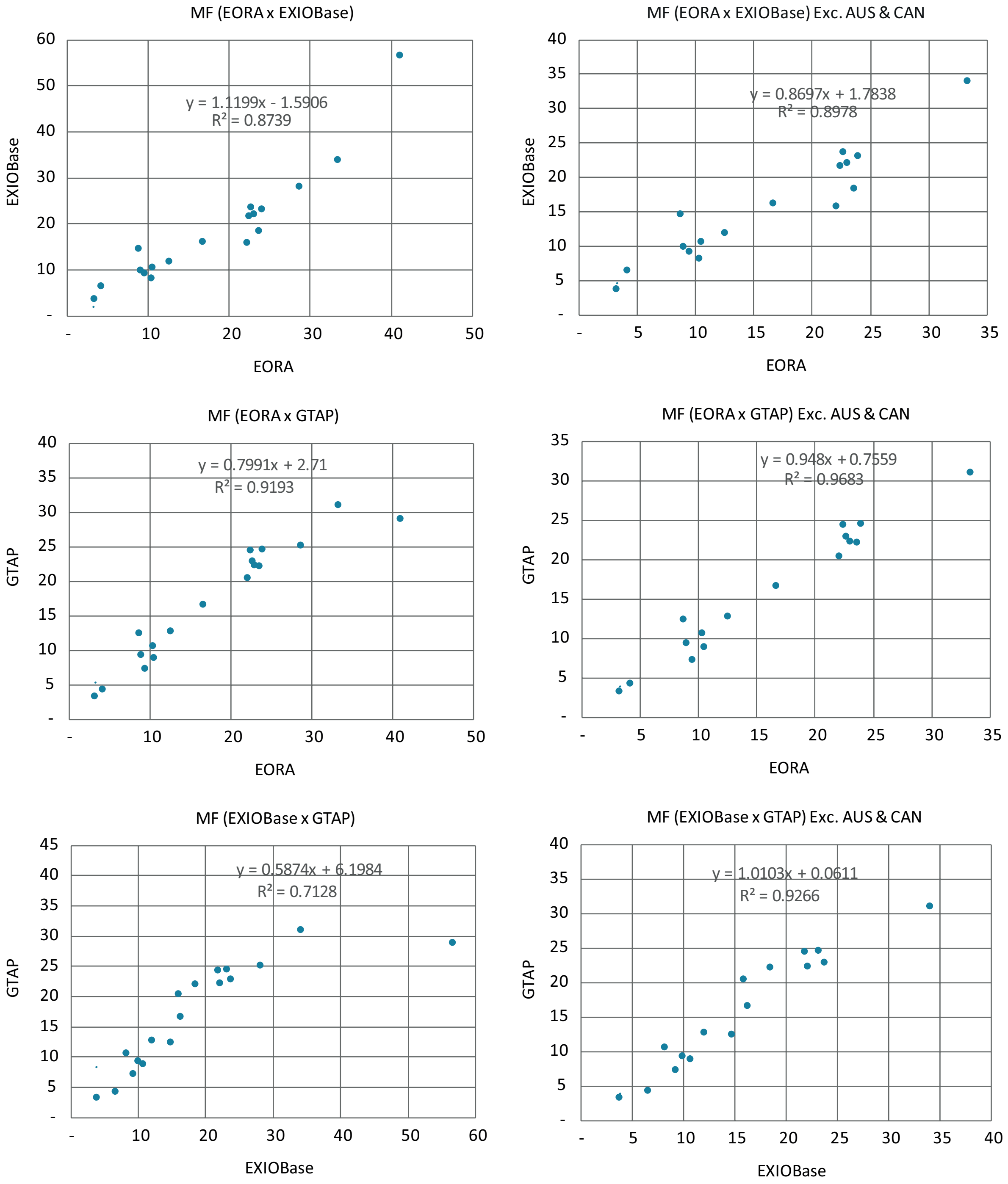
Panel 1. Material footprint of total final demand by broad economic sectors, 2007



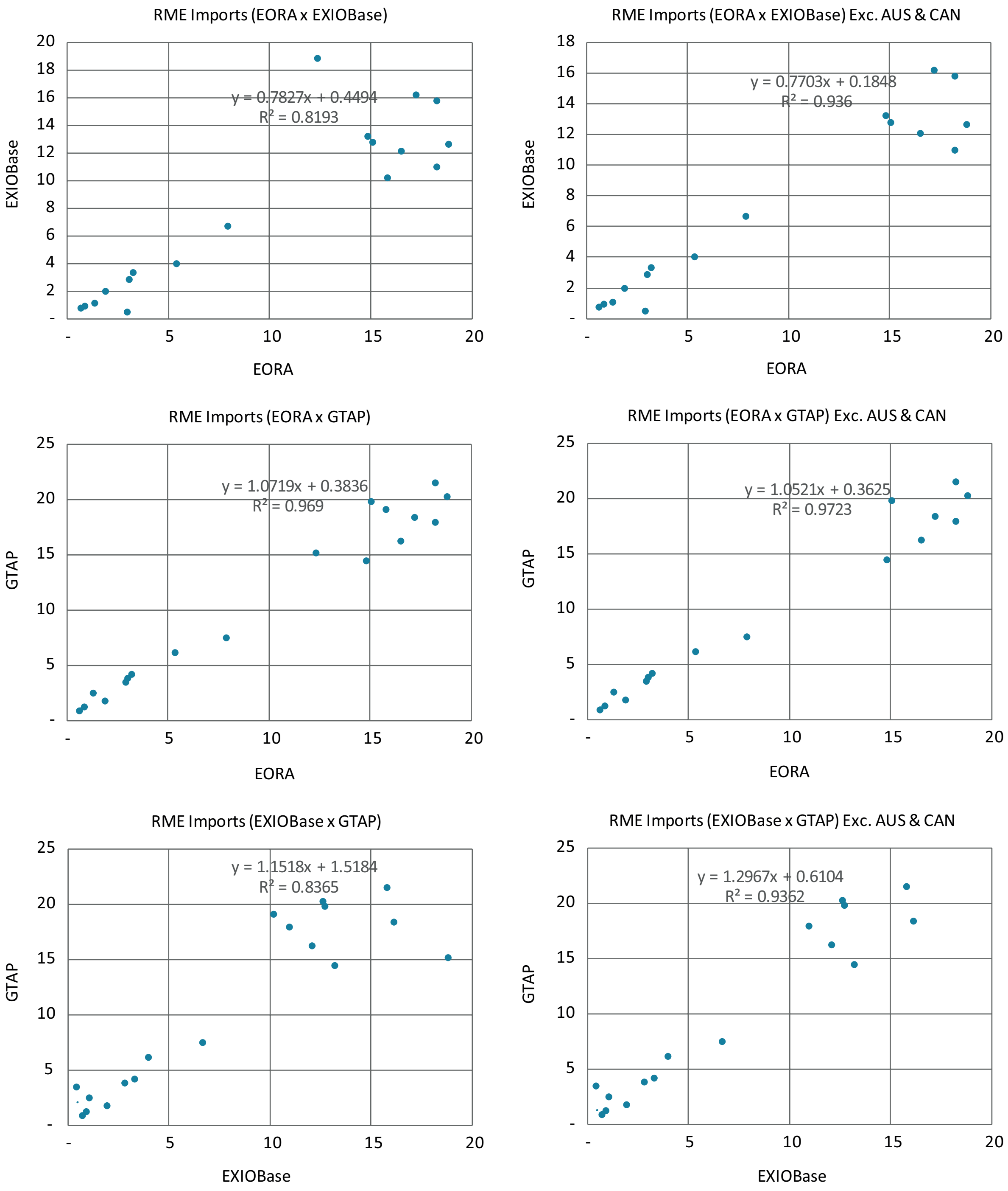
Panel 1. Material footprint of total final demand by broad economic sectors, 2007



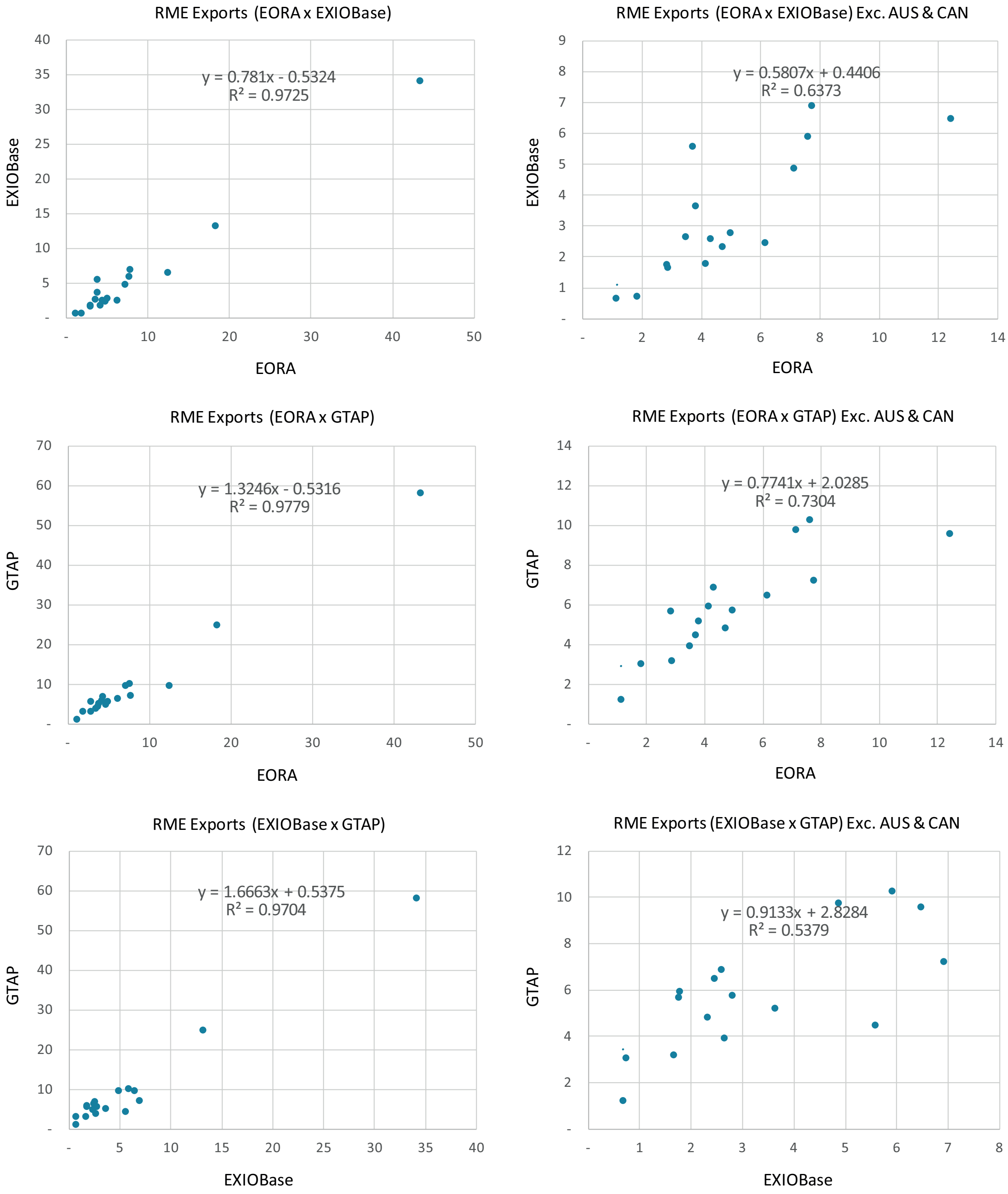
Panel 2. Regressions of material footprint for total final demand, comparing three MRIO frameworks, for 2007



Panel 3. Regressions of RME of Imports, comparing three MRIO frameworks, for 2007



Panel 4. Pairwise correlation of RME of Exports for total final demand for three MRIO frameworks, 2007



CHAPTER

8

The uncertainity of non-metallic mineral accounts

The uncertainty of non-metallic mineral accounts

Non-metallic minerals are by far the largest component of global material flows and have the highest level of uncertainty. Recent research by Miatto et al. (in review) has looked at an alternative and more precise way to account for extraction of non-metallic minerals using detailed engineering knowledge as a starting point. We use the results of the new study (Miatto et al. in review) to test the robustness and reliability of the non-metallic minerals extraction data that underpin this assessment study.

To account for global yearly consumption of aggregate, Miatto et al. (in review) used data for the apparent consumption of cement, bitumen and bricks, plus data on railway construction, as a starting point and hence used a similar methodological approach to this study to account for non-metallic minerals extraction.

In Miatto et al. (in review) each material category has been multiplied by a coefficient derived from engineering knowledge and consultations with experts from the construction sector, in order to unpack the correlation between some well-accounted materials and the related consumption of non-metallic minerals. The resulting coefficients are summarized in Table 9:

Table 9. Summary of the intensities applied to five construction categories

Concrete	Roads	Bricks	Sub-layers	Railways	Cement
$\lambda_{concr} = 5.26$	$\lambda_{road} = 51.12$	$\lambda_{brick} = 1.16$	$\lambda_{sub} = 0.42$	$\lambda_{rail,y,i} = 2119.3 \cdot g_i - 581.2$	$\lambda_{cem} = 1.57$

The study also offers uncertainty ranges by changing the frequency functions for concrete and road design. This allows to assess uncertainty ranges for the account of non-metallic minerals extraction. For concrete, the coefficient varies between a minimum of λ_{concr}=4.73 (assuming an even use of all possible types of concrete) and a maximum of λ_{concr}=5.90 (a case where over half of all concrete would be the weakest type, i.e. C16/20).

For roads, the minimum coefficient is λ_{road}=50.78 (assuming the lowest soil resistance, i.e. 20 MPa, for more than half of all cases) and the maximum is λ_{road}=52.74, (which is the case when all roads are built on hard soil, i.e. high soil resistance of 70 MPa).

For gravel in building sub-layers, the literature (Tanikawa et al. 2015) suggests that the amount of gravel for foundations varies between 5 to 10% of the building concrete weight, depending on the location, function, and size of the construction, which provides a quite narrow uncertainty range. Miatto et al. (in review) did not establish uncertainty ranges for bricks and cement production; these are, however, of less importance with regard to magnitude. Uncertainty was assessed based on the range of fluctuation for concrete and roads, which constitute 80% of non-metallic minerals extraction. Miatto et al. (in review) arrive at an uncertainty range of 1 billion tonnes equal to and cement production which are, however, of less importance with regard to magnitude, function, and size of the construction.

Figure 82 shows the global extraction of non-metallic minerals from the study of Miatto et al. (in review), starting at around 10 billion tonnes in 1970 and reaching about 35 billion tonnes in 2010, a 3.5-fold growth and a yearly average growth rate of 3.4%.

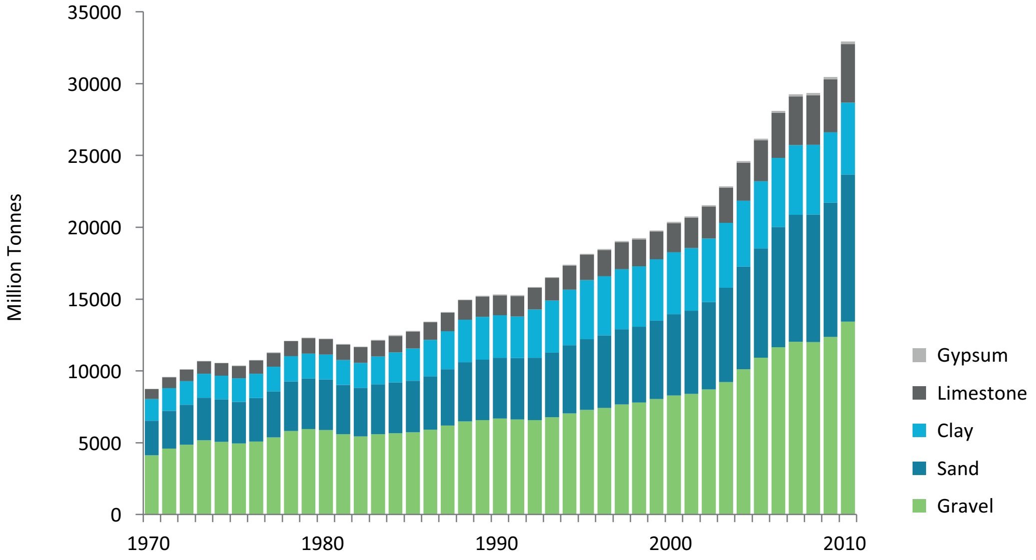


Figure 82. Global extraction of non-metallic minerals by type, 1970–2010, million tonnes

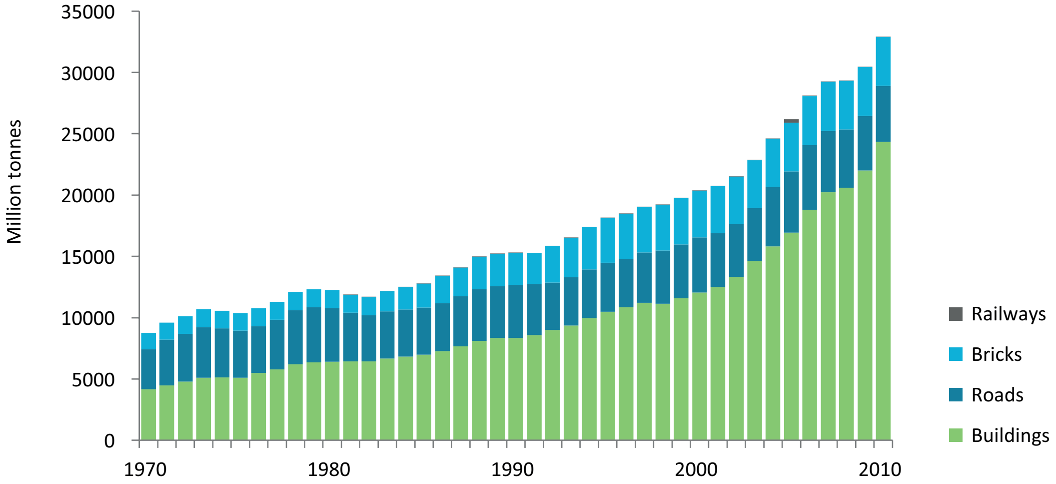


Figure 83. Global extraction of non-metallic minerals by sector of use, 1970–2010, million tonnes

Sand and gravel constituted the main share of global non-metallic minerals extraction in 2010 (40.8% gravel and 31.1% sand). Limestone, for cement production, had the fastest average annual growth rate of 4.5%, gravel extraction grew by 3.7% per year, and clay extraction grew by 3% per year.

Figure 83 shows the relative importance of use of non-metallic minerals by sector. Concrete in buildings[13] is the largest contributor to the use of sand and gravel by sector. Concrete in buildings comprises 40.8% gravel and 31.1% sand. Limestone, for cement production, had the fastest average annual growth rate of 4.5%, while gravel extraction grew by 3.7% per year. Non-metallic minerals for roads and bricks are of a similar magnitude and show a slower average growth rate compared to non-metallic minerals for buildings. The average annual growth rate for roads was 0.8%, compared to 2.8% for bricks. The amount of non-metallic minerals required for rail tracks is negligible.

Comparison of Miatto et al. (in review) with this study

Figure 84 shows a comparison of the global non-metallic minerals extraction for this study and Miatto et al. (in review). While our study reports lower extraction amounts for the 1970s it lies close to the lower confidence range of the Miatto et al. account. Over time, the difference between the two accounts becomes smaller. One reason for the higher extraction data in Miatto et al. is a more thorough assessment of brick production and the associated amounts of clay.

At the regional level, the two data sets show some differences for most world regions. Miatto et al. have higher extraction data for Asia and the Pacific for the whole four decades and substantially higher for the EECCA region for the 1970s and 1980s, and somewhat higher for Latin America and the Caribbean for the whole time period.

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[13] Buildings include the actual buildings, and other infrastructure such as dams, water tanks, bridge pillars, and so on.

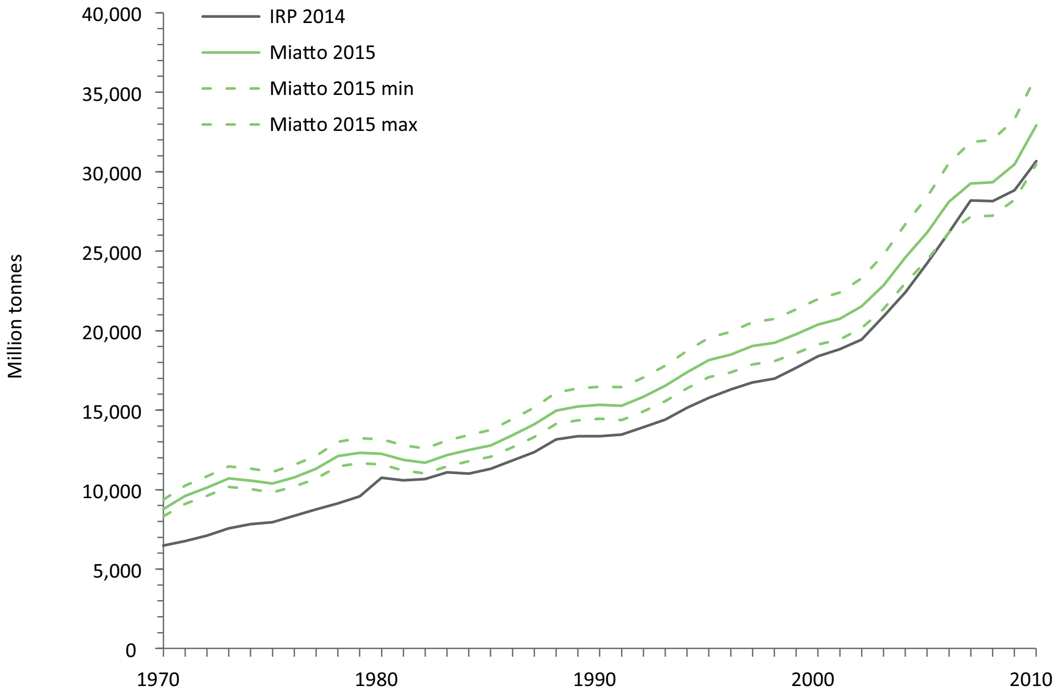
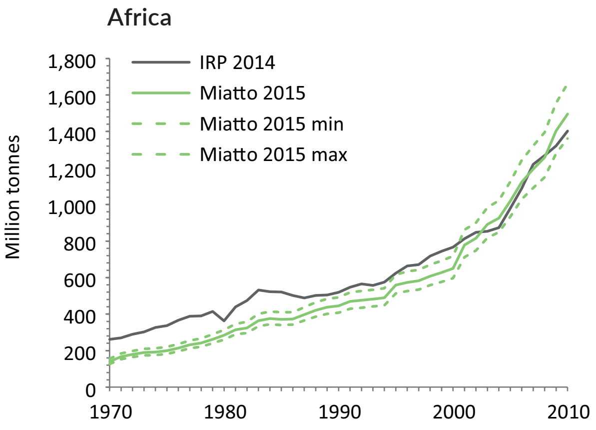


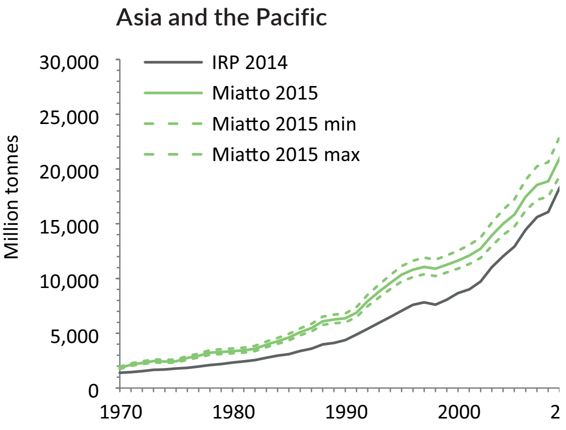
Figure 84. Comparison on the global level

This study has higher extraction data for Europe and North America since 1980 but lower extraction data for the 1970s compared to Miatto et al. (in review). Overall, the closeness of the two accounts raises confidence in the non-metallic mineral accounts presented in this assessment study but also show the additional effort that is needed in this domain of material flow accounts.

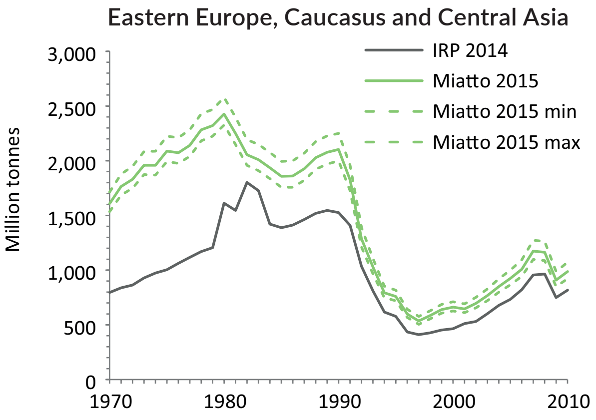
Figure 85 below shows a comparison between the figures for non-metallic minerals extraction of Miatto et al. (in review) and this study for the seven world regions.



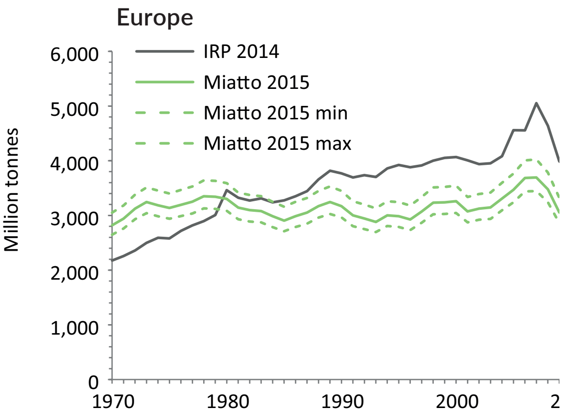
Africa



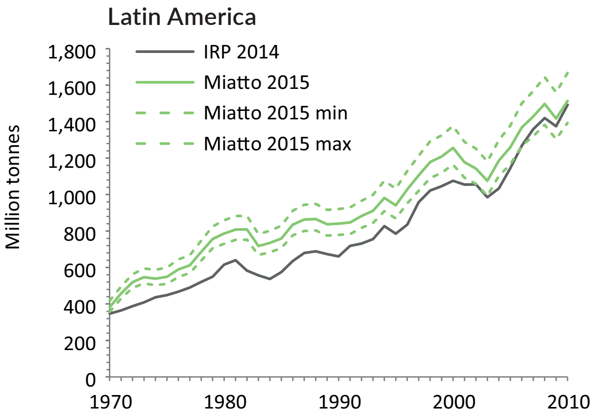
Asia and the Pacific



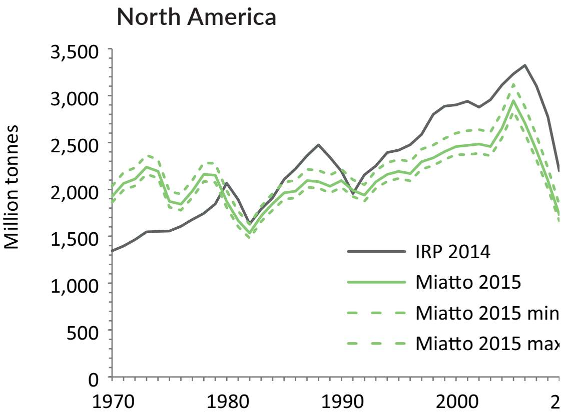
Eastern Europe, Caucasus and Central Asia



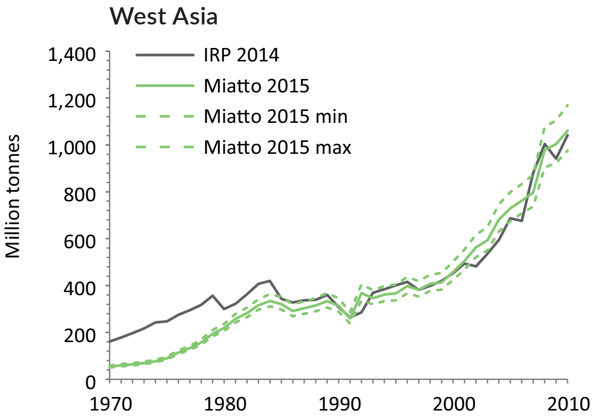
Europe



Latin America



North America



West Asia

Figure 85. Comparison of non-metallic minerals extraction of Miatto et al. (in review) and this study for the seven world regions

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Technical annex

Main principles of material flow accounts

Material flow accounts consist of a number of accounting modules related to specific indicators.

- The first module is concerned with domestic material extraction (DE), and direct imports (IM) and exports (EX) of materials.
- The second module focuses on indirect flows associated with imports and exports, i.e. the raw material equivalents of imports (RMEIM) and exports (RMEEX).
- A third module looks at the output side of the material flow accounts and reports domestic processed output (DPO), i.e. flows of waste and emissions and the gateways through which they leave the economy towards the environment (landfill, soil, water and air).
- The fourth module measures net additions to stocks (NAS) and may contain a stock account of in-use stock (Stock) and allows for closing the material flow balance by linking inputs to outputs and by introducing a set of balancing items.
- The fifth module looks at unused extraction that occurs in the context of domestic extraction in a target economy or with regard to the raw material extraction related to imports and exports abroad.
- A sixth module would focus on the material flows of different economic sectors and would create a true material flow satellite account and is related to the creation of physical input-output tables.

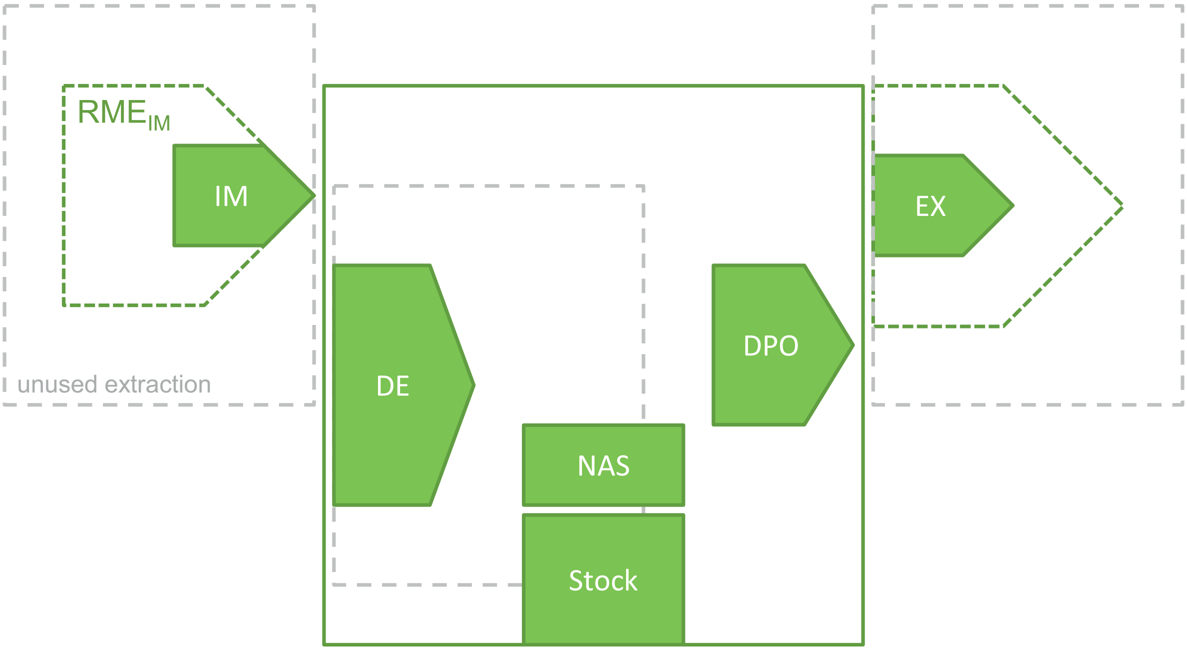

Figure 86. Structure of national material flow accounts

Each accounting module yields a set of indicators.

Module 1: The data set established in module 1 allows for five main indicators which are the core set of material flow indicators. They include domestic extraction (DE) of materials which are further used in economic processes usually accounted for at the point when the natural resource becomes commoditized and a price is attached. Imports (IM) and exports (EX) of materials are measured at the volumes at which they cross national boundaries. They may contain materials at different stages of processing including unprocessed primary products, processed primary products, simply transformed manufactures and elaborately transformed manufactures. With this information additional indicators can be derived including Physical Trade Balance (PTB) and Domestic Material Consumption (DMC) where PTB = IM – EX and DMC = DE + IM – EX = DE + PTB. The additional indicator Direct Material Input (DMI) has not been calculated for this report, but DMI = DE + IM.

Module 2: The data set established in module 2 is based on the global account for DE and attributes DE to final consumption of each country using a multi-regional, global input-output (MRIO) framework. The derived indicators include the raw material equivalent of imports (RME_{IM}) and raw material equivalent of exports (RME_{EX}) which include the upstream material requirements to produce direct imports and exports. RMEs assume a similar system boundary (point of extraction and commodification) for domestic and traded materials. The raw material trade balance (RTB) is established by subtracting RMEEX from RMEIM. With this information the material footprint of consumption (MF) indicator is established which attributes global material extraction (wherever it occurs and along the whole lifecycle of resources) to final demand in a country where MF = DE + RMEIM – RMEEX = DE + RTB.

Module 3: The data set for module 3 was not established for this report. It would contain the amounts of waste going to landfill, emissions to air and emissions to water. It would allow the establishment of an indicator for domestic processed output (DPO) and indicators for DPO_{land}, DPO_{air} and DPO_{water} where $DPO = DPO_{land} + DPO_{air} + DPO_{water}$.

Module 4: The data set for module 4 was not established for this report. It would have allowed the calculation of net additions to stock NAS where NAS = DMC – DPO + balancing items on the input and output sides. There are different additional ways to account for NAS based on stock and flow modelling. Module 4 would also contain data on the extent of in-use material stocks, which would add a stock perspective to the material flow accounts. Stocks would be reported by material and asset characteristics, including life tables for major assets.

Module 5: There was also no investigation of unused extraction of materials, i.e. materials that are mobilized but do not enter the economy, undertaken for this report. Unused extraction in volume is often the same size as used extraction reported in this report but data for unused extraction have a higher range of uncertainty. It is mostly not reported in official statistics and requires estimation techniques and modelling.

Module 6: Satellite accounts for material flows are an important step which has not been undertaken for this report. They require additional data and modelling. The physical data that would underpin sectoral material use are often not available in official statistics. It would perhaps require the formation of a physical input-output table of the economy (PIOT) to support establishment of sectoral accounts for material flows.

In the context of the System of Environmental-Economic Accounting (SEEA) material flow and stock accounts could be related to natural resource accounts which may include agricultural land, forest and fish stocks, fossil fuel and minerals reserves.

Table 10. List of material flow and stock indicators

Abbreviation	Indicator name	Accounting module
DE	Domestic material consumption (used in the economy)	Module 1
IM	Imports of materials (direct)	Module 1
DMI	Domestic material input (DE + IM)	Module 1
EX	Exports of matrerials (direct)	Module 1
PTB	Physical trade balance (IM – EX)	Module 1
DMC	Domestic material consumption (DE + PTB)	Module 1
RME_{IM}	Raw material equivalents of imports (of such imports that service domestic final demand)	Module 2
RME_{EX}	Raw material equivalents of exports	Module 2
RTB	Raw material trade balance	Module 2
MF	Matreial footprint	Module 2
DPO	Domestic process output	Module 3
NAS	Net additionas to stock	Module 4
MS	Material stock	Module 4
DE_{unused}	Unused domestic material extraction (returned to the environment without economic use)	Module 5
TMI	Total material input (DE + DE_{unused} + RMEIM)	Module 5
TMR	Total material requirement (DE + DE_{unused} + RTB)	Module 5
	Full PIOT showing sectoral material flow indicators	Module 6

Accounting methods and data sources

Biomass

Global MFA data on biomass extraction are commonly derived from the databases of the United Nations Food and Agricultural Organization, and compiled in accordance with standard MFA methods (see Eurostat 2013, Fischer-Kowalski et al. 2011). The three global MFA databases from the CSIRO, the WU, and the SEC that build the basis for the global database presented here, follow these harmonized concepts and methods. Table 11 gives an overview of the data sources and underlying primary data used for the respective calculations. The CSIRO, SEC and WU databases were very similar with respect to the MFA categories primary crops, wood extraction and fish catch. They differed considerably for crop residues, fodder crops and grazed biomass, which make up feed/roughage for animals. These three categories are complementing variables used in the feed gap or grazing gap calculation. Two different modelling approaches for the category grazing can be distinguished: (1) calculating a grazing gap based on livestock numbers and their feed demand or (2) calculating an energy feed gap between the animal products produced and the amount of feed energy embodied in these products. We opted for the second approach as it prompts the provision of more accurate data.

Data sources

Biomass data comprise six subcategories: crops, crop residues, grazed biomass, fodder crops, wood, and animal products. Data on agricultural and forestry harvest were extracted from the United Nations Food and Agricultural Organization's statistical database (FAO 2014c, FAO 2014b). Data on fish capture were extracted from the FAO's Fisheries and Aquaculture database (FAO 2014a).

Table 11. Overview of data sources by MFA categories

Category	Years	Data source
Crops (Cereals, Other crops, Roots and tubers, Sugar crops, Pulses, Nuts, Oil bearing crops, Vegetables, Fruits, Fibres)	1970–2010	FAOSTAT
Crop residues	1980–2010	FAOSTAT, taken from WU database
	1970–1979	FAOSTAT, newly calculated
Grazed biomass		provided by CSIRO
Fodder crops		FAOSTAT
Wood (Timber, Wood fuel and other extraction)	1970–2008	FAOSTAT, taken from CSIRO database, adjusted to include bark
	2009–2010	FAOSTAT, newly calculated
Animal products	1980–2010	FAO Fishstat, taken from WU database
(Wild aquatic animals)	1970–1979	FAO Fishstat, newly calculated

Accounting methods

Crops

Data taken directly from the FAO production statistics. No further calculations applied.

Crop residues

Crop residues are a by-product from agricultural harvest. Parts are further used as fodder or as straw and other parts are left unused. Only the used fraction of crop residues has to be considered in MFA and thus is accounted for. In a first step the harvested biomass is multiplied with a harvest factor to account for the "fall-out", which contains by-product feed, by-product straw and unused biomass. The used by-product fractions are transformed to a moisture content of 15%. The applied factors for harvest, straw, feed and unused biomass stem from two publications, i.e. Jölli and Giljum (2005) and Krausmann et al. (2009). Dry matter factors derive from Wirsenius (2000).

Fodder crops and grazed biomass

Fodder crops data are sourced from FAO online database at FAO (2014c), and include all classes of crops from the "Crops, Primary" list prefaced with "Forage and silage,", e.g. "Forage and silage, legumes", "Forage and silage, maize". They do not include any other crops, regardless of whether some portion of them may have been used as animal feed.

As there is very little direct information on tonnages of grazed biomass, it has been is modelled by calculating a "feed gap". The feed gap is the deficit between the energy required to produce recorded animal products from ruminant animals, and that which can be accounted for from inputs other than grazing. The energy gap is then translated into a tonnage of grazed biomass.

Estimating the initial feed gap is a multistage process:

- First, the total amount of animal products "grown" in a country was calculated, starting with animal products recorded in FAO (2014c), then subtracting/adding to this the animal product equivalent of live animals imported/exported, derived via animal numbers and carcass weights from the same FAO source.
- The feed energy required for each country's animal product output was then estimated by applying the feed energy requirements per kg of animal product to the (live trade corrected) output in each animal product. Regionally specific conversion coefficients for product -> feed energy from Wirsenius (2000) were used.
- Tonnages for those primary crops recorded as going to animal feed in FAO (2014a) for each country were then converted into their equivalent in feed energy available to each class of animal. The conversion factors used here were also derived from Wirsenius (2000). To this available energy was added the energy available from fish used as feed, also sourced from FAO (2014b).
- The figure derived for total available feed energy in each country was then hierarchically allocated to different classes of animal, i.e. first claim on any crops compatible with poultry was given to poultry, until their requirements were met. Pigs had second claim on any crops compatible with poultry and/or pigs and/or ruminants. If any feed crops remained after the requirements for pigs were met, ruminants received the remainder.
- Any deficit between the energy available from crops allocated to feed ruminants, and the energy requirements for ruminant product output, is assumed to be filled next from the specific forage crops listed previously.
- If a feed gap remains for ruminant animal products output after forage crops have been accounted for, the remainder is assumed to come from grazed biomass. Importantly, no role for crop residues is been considered[14]. This energy deficit filled from grazing is then converted to tonnes of grazed biomass required, using the energy content for "permanent pasture, over sown" for the relevant region for each country derived from Wirsenius (2000) as a conversion factor, and assuming a 15% moisture content.

While fodder crops and grazed biomass are listed as two distinct categories, in reality separating the two is very difficult in practical terms, even though conceptually simple. Ideally, fodder crops should be restricted to those crops specifically grown and harvested for ruminant forage and silage. Unfortunately, the available data used for fodder crops appear to suffer from two major problems. The first is the uncertain basis on which weight is determined with regard to moisture content. This is a major problem, as crops in this class can have much higher than the 15% moisture assumed as a

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[14] Substitution of crop residues for grazed biomass was not estimated due to the lack of sufficient data on the proportions of each specific crop residue going to feed. Good data on this would be required to make reasonable estimates of the remaining "grazing gap" due to the highly non-linear response of ruminant productivity to feed energy density at lower values. The energy available for growth (i.e. beef production) can vary over eightfold depending on whether the crop residue is a higher energy variety like sugar beet tops, or low energy variety like rice straw. Where a tonne of sugar beet tops would substitute for a tonne of the reference grazed pasture used in this study, over six tonnes of rice straw would be required to produce the same beef output as one grazed tonne.

standard accounting basis, and upon which all feed energies have been calculated. The second is that it appears unlikely that there has been clear separation between forage crops which are grazed directly in the field, and those which have been harvested and converted to silage or hay. It is thus likely that where no grazed biomass is apparently required after fodder crops have been allocated, this is because some of the fodder crops recorded actually had a moisture content higher than 15%, and/or it was actually grazed in situ. It is most unlikely that no biomass at all was grazed.

Wood

Data for the extraction of wood are reported in the FAO forestry statistics (FAO 2014a) in volumetric units. The transformation to tonnages was done by applying the default densities supplied in Eurostat (2009) for coniferous and non-coniferous woods at a moisture content of 15%. The resulting wood extraction was further multiplied with a bark factor of 1.1 to account for used bark (Eurostat 2013).

Animal products

The category "animal products" comprises all wild catch of aquatic animals. According to standard MFA methods, fish derived from aquaculture is not accounted for. Data for fish catch are taken from the Global Production Statistics of the FAO Fisheries and Aquaculture Department (FAO 2014a). Some of the data in the FAO database is not reported in tonnes but in numbers of caught animals (e.g. whales, seals and other aquatic mammals); these values are transformed to tonnes using the following average factors: blue-whales and fin-whales at 100 tonnes, seals and walruses at 0.5 tonnes and sperm-whales and pilot-whales at 15 tonnes.

Fossil fuels

Data on fossil fuel extraction are taken from energy statistics stemming from three international databases and integrated into one consistent data set. The primary sources are the World Energy Statistics and Balances of the International Energy Agency (IEA 2014b), the United Nations Energy Statistics Database (UNSD 2015) and the International Energy Statistics of the US Energy Information Administration (EIA 2015). From all three sources the most recent data were used.

The IEA data set is the most comprehensive currently available data set reporting on fossil fuel extraction and energy use of all countries worldwide. Data can be easily compiled and retrieved online (IEA data are not free of charge). Data from UNSD were retrieved in two different data sets. This is because years prior to 1990 are not available online at the United Nations data portal and have to be purchased. Data from EIA is freely available online.

Integration of data

Data have been integrated into one data set giving highest priority to IEA data, which were first complemented with data from UNSD and after that with data from EIA. A relatively strict scheme was applied for the scope of complementation, i.e. data from UNSD were added only in those cases where IEA did not provide any values and were only used for replacement where its time coverage (for a single commodity of a single country) was at least more than half of that of IEA data. The same approach was used to complement that integrated data set with data from EIA.

Table 12 illustrates the commodities derived from each primary database and the applied concordance.

Table 12. Commodities derived from each primary database and concordance applied

IEA	UNSD	EIA	IRP database
Hard coal (if no detail)		Hard Coal	
Brown coal (if no detail)			
Anthracite	Anthracite	Anthracite Coal	Anthracite
Coking coal	Coking coal		Coking coal
Other bituminous coal	Other bituminous coal	Bituminous Coal	Other bituminous coal
Sub-bituminous coal	Sub-bituminous coal		Sub-Bituminous coal
Lignite	Lignite	Lignite Coal	Lignite / Brown Coal
Peat	Peat		Peat
Crude/NGL/feedstocks (if no detail)			
Crude oil	Conventional crude oil	Crude Oil including Lease Condensate	Crude oil
Natural gas liquids	Natural gas liquids	Natural Gas Plant Liquids	Natural gas liquids
Natural gas	Natural gas (including LNG)	Dry Natural Gas	Natural gas

For the purpose of consistency, data from the three different sources were not mixed for a single commodity for one country. However, within a single country different commodities can have different primary data sources. Due to the different classification of coal between IEA and EIA there was a risk of double counting. In order to avoid any errors stemming from that issue, no data on coal from EIA were included, except for those countries where IEA did not provide any data for coal. Data for coal extraction from UNSD was not included in the data set because none of the coal commodities reported by UNSD exceeded the time coverage of data reported by IEA.

The integration of data has shown that data from IEA is comprehensive to such an extent that complementation from the other two sources occurred only in a few cases. Table 13 illustrates the relative shares in total data points of primary data used in the data set (by primary database).

Table 13. Relative shares in total data points of primary data used in the data set (by primary database)

Database	Share
IEA	88.2%
UNSD	7.4%
EIA	4.4%

Data adjustment and estimations

Conversion

The IRP database provides all values in 1000 tons. Therefore primary data which were reported in other units had to be converted using factors published by the same primary sources. The IEA and UNSD report all categories relevant for the IRP Global Material Flow database in primary units of 1000 tons, except for natural gas which had to be converted from TJ into 1000 t (kt), using a conversion factor provided by IEA (0.018 kt/TJ). Table 14 provides all factors used to convert reported physical units to metric tons.

Table 14. Factors used to convert reported physical units to metric tons

Primary data	Commodity	Unit (primary data)	Factor used	Source (of factor)
IEA	Natural gas	Terajoule	0.018	IEA
EIA	Natural gas	Billion cubic feet	19.5228	IEA (kt/TJ) EIA (TJ/cubic feet)
EIA				
EIA	Coal	Short ton	0.9072	EIA
EIA	Oil	Barrel / day	0.04979	EIA
EIA	Natural gas liquids	Barrel / day	0.0351	EIA

Estimations

IEA provides data for the years 1971 to 2012. Therefore values for the year 1970 were estimated by applying a linear extrapolation based on the trend of the following four years.

IEA does not report disaggregated data on coal extraction for years prior to 1978. Instead the two categories “Hard Coal” and “Brown Coal” are used. These two categories were disaggregated into their respective subcategories using the average relative shares of the years 1978 to 1987. According to IEA (2014a) “Hard Coal” comprises “Anthracite”, “Coking coal” and “Other bituminous coal” and in some cases “Sub-bituminous coal”, while “Brown Coal” comprises “Lignite” and in some cases “Sub-bituminous coal”. However, documentation provided by IEA does not specify how “Sub-bituminous coal” is allocated for different countries. Therefore an approach was applied which compared aggregated values for the year 1977 and disaggregated values for the year 1978, determining where “Sub-bituminous coal” had been allocated to.

EIA provides data for the years 1980 to 2012; hence, data for the time range 1970 to 1979 had to be estimated. This was done by calculating average fuel intensities (fossil fuel per unit of GDP) for the years 1980 to1984 and applying those to the GDP data of the missing years.

Adjustment of geographical scope

The IRP database reports data for the Soviet Union and former Yugoslavia until 1991 and for its successor states from 1992 on. Data for Czechoslovakia are reported until 1992 and for its successor states from 1993 on. Therefore data from IEA and UNSD were adjusted accordingly.

Metal ores

The data set on extraction of metal ores was composed following the standards on material flow accounting (MFA) published by Eurostat and the OECD between 2001 and the present time (Eurostat 2001, 2007, 2012, 2013; OECD 2004, 2008).

Data sources

Primary data on the extraction of metal ores were obtained from three comprehensive international data sources: the British Geological Survey (BGS 2015), the United States Geological Survey (USGS 2015) and the World Mining Data (WMD) published by the Austrian Ministry for Science, Research and Economy (Reichl et al. 2015). All data sets are available for free online. BGS provides an online download tool, USGS provides Excel files and pdf country sheets and the WMD are published in pdf format. All data sources provide data annually, normally with a delay of 2 to 3 years (t–2, t–3).

Integration of data

Data from these sources were integrated into one consistent data set, using the BGS database as the main data source and complementing with the other two data sources. Hence, data from the other two sources were used in those cases where BGS does not report values for the extraction of a commodity in a country. In most cases, the time series of each commodity in a specific country is based on one main data source. Only in a small number of cases was an additional data source used, mainly to extend time series starting later than 1980.

Aggregation of data

The following table provides the concordance between the commodities derived from the primary sources and their aggregation into the raw material groups used in the IRP data set. Data for 32 types of metals were collected and aggregated into 10 metal ore groups.

Table 15. Concordance between primary data on metal ores and the IRP database

Primary database	Commodity	IRP category
BGS	Bauxite	Bauxite and other aluminium ores – gross ore
	Copper, Mine	Copper ores – gross ore
	Gold, Mine	Gold, silver, platinum and other precious metal ores – gross ore
	Platinum Group Metals, Mine	
	Silver, Mine	
	Iron Ore	Iron Ores
	Lead, Mine	Lead ores – gross ore
	Nickel, Mine	Nickel ores – gross ore
	Antimony, Mine	Other metal ores – gross ore
	Arsenic, White	
	Beryl	
	Bismuth, Mine	
	Cadmium	
	Chromium Ores And Concentrates	
	Cobalt, Mine	
	Germanium Metal	
	Lithium Minerals	
	Magnesium Metal, Primary	
	Manganese Ore	
	Mercury	
	Molybdenum, Mine	
	Rare Earth Minerals	
	Selenium Metal	

Primary database	Commodity	IRP category
	Tantalum And Niobium Minerals	
	Tellurium Metal	
	Titanium Minerals	
	Tungsten, Mine	
	Vanadium, Mine	
	Zirconium Minerals	
	Tin, Mine	Tin ores – gross ore
	Uranium	Uranium and thorium ores – gross ore
	Zinc, Mine	Zinc ores – gross ore
USGS	Alumina	Bauxite and other aluminium ores – gross ore
	Antimony	Other metal ores – gross ore
	Ferrochromium	
	Ferroniobium (Ferrocolumbium)	
	Manganese Ore	
	Selenium	
	Copper	Copper ores – gross ore
	Gold	Gold, silver, platinum and other precious metal ores – gross ore
	Silver	
	Iron Ore	Iron Ores
	Lead	Lead ores – gross ore
	Nickel	Nickel ores – gross ore
	Tin	Tin ores – gross ore
	Uranium	Uranium and thorium ores – gross ore
	Zinc	Zinc ores – gross ore
WMD	Aluminium	Bauxite and other aluminium ores – gross ore
	Bauxite	
	Copper	Copper ores – gross ore
	Gold	Gold, silver, platinum and other precious metal ores – gross ore
	Silver	
	Platinum group metals (palladium, platinum, rhodium)	
	Iron	Iron Ores
	Lead	Lead ores – gross ore
	Nickel	Nickel ores – gross ore
	Antimony	Other metal ores – gross ore
	Arsenic	

Primary database	Commodity	IRP category
	Bismuth	
	Cadmium	
	Chromium	
	Cobalt	
	Germanium	
	Lithium	
	Mercury	
	Molybdenum	
	Rare Earth Metals	
	Tungsten	
	Vanadium	
	Manganese	
	Titan	
	Zirconium	
	Tin	Tin ores – gross ore
	Uranium	Uranium and thorium ores – gross ore
	Zinc	Zinc ores – gross ore

Estimation of gross ore from data on net metal contents

Data on metal production compiled by geological institutes or statistical agencies are often reported in terms of net metal contents, i.e. metal quantity after the processing and concentration of crude ores. However, according to MFA standards, metal extraction should be accounted as crude ores, i.e. the overall amounts of extracted metal ores before processing and concentration. Therefore, in cases where no data on gross ore extraction but only data on net metal content are reported estimations are required, in order to transform all reported net metal content values into equivalents of gross ores.

The concentrations in which metals occur in primary ores in nature can differ considerably between countries and mines. This requires applying (at least) country-specific information on average metal concentrations in order to obtain robust estimates of the corresponding amounts of extracted crude ore. Information on metal concentrations was obtained from a large number of publications by different geological surveys, ministries and other institutions. In addition, correspondence was exchanged with experts from relevant agencies (e.g. USGS) and all factors were revised and cross-checked within the project team. An overview of the sources used for ore grades is shown in Table 16 below.

In those cases where data on extraction of a metal in a country were available, but no respective factor to estimate the gross weight could be found, different types of proxy values were applied. Depending on the specific case, either an available factor for a neighbouring country or regional (i.e. country group / continent) or global average factors were applied. If none of these were available, regional or global average factors were calculated based on existing information.

Table 16. Sources used for the compilation of metal ore grades applied in the IRP database

Metal	Institution/Author	Publications
Antimony	US Geological Survey	USGS – Country Reports
		Personal Communication
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
Bauxite	Federal Institute for Geosciences and Natural Resources, Germany	Geological yearbook, SH 2, Aluminium
		Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
		Studies on supply and demand of mineral raw materials
	US Geological Survey	USGS – Country Reports
Beryllium	Federal Institute for Geosciences and Natural Resources, Germany	Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished manuscript.
Chromium	Federal Institute for Geosciences and Natural Resources, Germany	Geological yearbook, Chromium
		Studies on supply and demand of mineral raw materials
Cobalt	US Geological Survey	Personal Communication
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
Copper	Bureau of Mines	The availability of primary copper in market economy countries. United States Department of the Interior. IC 9310.
	Federal Institute for Geosciences and Natural Resources, Germany	Geological yearbooks
		Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
		Studies on supply and demand of mineral raw materials XI
	Mudd, G.	The sustainability of mining in Australia: key production trends and their environmental implications. Melbourne, Department of Civil Engineering, Monash University and Mineral Policy Institute.

Metal	Institution/Author	Publications
	US Geological Survey	USGS – Country Reports
		Personal Communication
	Wuppertal Institute	Database of Wuppertal Institute (WI)
Gold	Federal Institute for Geosciences and Natural Resources, Germany	Geological yearbooks
		Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	Mudd, G.	The sustainability of mining in Australia: key production trends and their environmental implications. Melbourne, Department of Civil Engineering, Monash University and Mineral Policy Institute.
	US Geological Survey	USGS – Country Reports
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
	Wuppertal Institute	Database of Wuppertal Institute (WI)
Iron ores	Federal Institute for Geosciences and Natural Resources, Germany	Geological yearbook
		Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	US Geological Survey	Iron ore statistical compendium
		USGS – Country Reports
		Personal Communication
Lead	Federal Institute for Geosciences and Natural Resources, Germany	Geological yearbook
		Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	Mudd, G.	The sustainability of mining in Australia: key production trends and their environmental implications. Melbourne, Department of Civil Engineering, Monash University and Mineral Policy Institute.
	US Geological Survey	USGS – Country Reports
	Wuppertal Institute	Database of Wuppertal Institute (WI)
Lithium	Federal Institute for Geosciences and Natural Resources, Germany	Studies on supply and demand of mineral raw materials XXI
	US Geological Survey	USGS – Country Reports
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.

Metal	Institution/Author	Publications
Manganese	Federal Institute for Geosciences and Natural Resources, Germany	Geological yearbook
		Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	US Geological Survey	USGS – Country Reports
		Minerals Yearbook, Manganese
		Manganese ore statistical compendium
Mercury	Federal Institute for Geosciences and Natural Resources, Germany	Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	US Geological Survey	USGS – Country Reports
		Personal Communication
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
Nickel	Federal Institute for Geosciences and Natural Resources, Germany	Geological yearbook
		Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	US Geological Survey	USGS – Country Reports
		Personal Communication
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
Platinum group (PGM)	US Geological Survey	USGS – Country Reports
		Personal Communication
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
Rare Earth Metals	Schütz, H.	Technical Details of NMFA (Inputside) for Germany (Imports to Germany). Wuppertal Institute, Wuppertal.
Silver	Federal Institute for Geosciences and Natural Resources, Germany	Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
		Studies on supply and demand of mineral raw materials XI
	US Geological Survey	USGS – Country Reports
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.

Metal	Institution/Author	Publications
Tin	Bureau of Mines	Tin availability – market economy countries. United States Department of the Interior. IC 9086.
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
Titanium (including Ilmenite and Rutile)	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
Tungsten	Federal Institute for Geosciences and Natural Resources, Germany	Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	Schütz, H.	Technical Details of NMFA (Inputside) for Germany (Imports to Germany). Wuppertal Institute, Wuppertal.
	US Geological Survey	Personal Communication
Uranium	Federal Institute for Geosciences and Natural Resources, Germany	Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	US Geological Survey	USGS – Country Reports
Vanadium	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
Zinc	Federal Institute for Geosciences and Natural Resources, Germany	Rohstoffwirtschaftliche Länderstudien (Raw material country studies – in German)
	Mudd, G.	The sustainability of mining in Australia: key production trends and their environmental implications. Melbourne, Department of Civil Engineering, Monash University and Mineral Policy Institute.
	US Geological Survey	USGS – Country Reports
	Wagner, H., Weber, L.	Gesichtspunkte für die bergtechnische und bergwirtschaftliche Beurteilung von Vorkommen mineralischer Rohstoffe. Unpublished German manuscript.
	Wuppertal Institute	Database of Wuppertal Institute (WI)

Minerals

The data set on extraction of minerals was composed following the standards on Material Flow Accounting (MFA) published by Eurostat and the OECD between 2001 and the present time (Eurostat 2001, 2007, 2012, 2013; OECD, 2004, 2008).

Data sources

Primary data on the extraction of minerals were obtained from three comprehensive international data sources: the British Geological Survey (BGS 2015), the United States Geological Survey (USGS 2015) and the World Mining Data published by the Austrian Ministry for Science, Research and Economy (Reichl et al. 2015). All data sets are available free of charge online. BGS provides an online download tool, USGS provides Excel files and pdf country sheets and the WMD are published in pdf format. All data sources provide data annually, normally with a delay of 2 to 3 years (t–2, t–3).

Integration of data

Data from these sources were integrated into one consistent data set, using the BGS database as the main data source and complementing with the other two data sources. Hence, data from the other two sources were used in those cases where BGS does not report values for the extraction of a commodity in a country. In most cases, the time series for each commodity in a specific country is based on one main data source. Only in a small number of cases was an additional data source used, mainly to extend time series starting later than 1980.

Aggregation of data

The following table provides a concordance between the commodities derived from the primary sources and their aggregation into the raw material groups used in the IRP data set.

Table 17. Concordance between primary data on minerals and the IRP database

Primary database	Commodity	IRP category
BGS	Barytes	Chemical and fertilizer minerals
	Borates	
	Fluorspar	
	Phosphate rock	
	Potash	
	Sulphur (Frasch)	
	Sulphur (Pyrites)	
	Sulphur (Recovered)	
	Sulphur ore	
	Attapulgite	Clays and kaolin
	Bentonite	
	Fuller's Earth	
	Kaolin	
	Sillimanite minerals	
	Sepiolite	
	Crushed rock	Non-Metallic minerals – primarily construction
	Sand and gravel	
	Asbestos	Other mining and quarrying products n.e.c
	Diamond	
	Diatomite	
	Feldspar	
	Graphite	
	Gypsum and plaster	
	Magnesite	
	Mica	
	Perlite	
	Strontium minerals	
	Talc	
	Vermiculite	
	Wollastonite	
	Brine salt	Salt
	Brine salt & sea salt	
	Evaporated salt	
	Other salt	
	Rock salt	

Primary database	Commodity	IRP category
	Rock salt & brine salt	
	Salt in brine	
	Sea salt	
USGS	Barite	Chemical and fertilizer minerals
	Flourspar	
	Phosphate Rock, Basic Slag and Guano	
	Sulphur	
	Sulphur From Pyrites	
	Bentonite	Clays and kaolin
	Fuller's Earth	
	Kaolin	
	Kyanite And Related Materials	
	Ball Clay	
	Kaolin	
	Potter Clay	
	Special Clay	
	Common Clay	
	Igneous Rock	Non-Metallic minerals – primarily construction
	Limestone	
	Sandstone	
	Slate	
	Crushed Stone	
	Marble	
	Asphalt	
	Sand And Gravel	
	Celestite	Other mining and quarrying products n.e.c
	Asbestos	
	Diatomite	
	Feldspar	
	Gypsum	
	Industrial Sand and Gravel (Silica)	
	Mica	
	Natural Iron Oxide Pigments	

Primary database	Commodity	IRP category
	Peat	
	Pumice And Related Materials	
	Talc And Pyrophyllite	
	Industrial Sand	
	Calcite	
	Chalk	
	Dolomite	
	Diamonds, Gemstones	
	Diamonds, Industrial	
	Magnesite	
	Quartzite	
	Salt	Salt
WMD	Baryte	Chemical and fertilizer minerals
	Boron minerals	
	Fluorspar	
	Phosphates (incl. guano)	
	Potash	
	Sulphur	
	Bentonite	Clays and kaolin
	Kaolin (china-clay)	
	Asbestos	Other mining and quarrying products n.e.c
	Diamonds (gem/industrial)	
	Diatomite	
	Feldspar	
	Graphite	
	Gypsum and anhydrite	
	Magnesite	
	Mica	
	Perlite	
	Talc (incl. steatite and pyrophyllite)	
	Salt	Salt

Data sources and estimation procedures for construction minerals extraction

The extraction of construction minerals makes up a large share of overall global material extraction. However, only a few countries and world regions report comprehensive and high-quality data on the extraction of construction minerals such as sand and gravel. Examples are the EU-28, for which Eurostat reports MFA data, including construction minerals, and the USA, where USGS publishes data on a regular basis. For these countries, data were directly retrieved from the sources named above.

To complement the data set with data on the extraction of construction minerals for those countries where no official data are available, estimation procedures needed to be applied. In the development of the IRP database, two estimation procedures were applied: the first based on physical data on cement and bitumen production, the second based on per capita GDP numbers.

Estimation based on physical data

This estimation approach was applied for all countries for which the USGS regularly reports data on cement and the IEA reports data on bitumen (or asphalt) production. The coverage of these two data sets allows estimation of data on extraction of construction minerals for around 50% of all countries worldwide, including all large consumers in the developing world, such as China, India and Brazil.

The procedure follows the methodology introduced by Krausmann and colleagues (2009) and estimates the extraction of construction minerals separately for two main purposes: (1) the construction of buildings and (2) the construction of transport infrastructure such as roads and runways.

1. Concrete is the main product used for buildings and mainly consists of aggregates (sand and gravel), cement, water, and burnt lime as binder. We use the factor of 6.5 introduced by Krausmann et al. as the ratio between sand and gravel and cement per mass unit of concrete to transform the data on cement production to corresponding amounts of sand and gravel. Limestone requirements for cement production are estimated by applying a factor of 1.4 tonnes of limestone per tonne of cement produced.
2. Asphalt (or bitumen) is the main material used for the construction of transport infrastructure (e.g. roads). Also in this case, we refer to a factor introduced by Krausmann et al., stating that for the production of asphalt, bitumen and sand and gravel are mixed at a ratio of 1:20.

Estimation based on socioeconomic data

For all other countries, for which neither official data on the extraction of construction minerals nor data on cement and/or asphalt production for estimation purposes are available, an alternative estimation procedure was applied, based on an approach developed in the setup of the database www.materialflows.net. In the respective technical report (SERI and WU-Vienna 2014), a table is provided, which illustrates the relationship of certain levels of GDP per capita and annual per capita extraction values for construction minerals, starting from 0.3 tonnes per capita per year for the least developed countries up to 10 tonnes per capita for high-income countries. The annual per capita extraction numbers at certain levels of GDP per capita were then multiplied by the total population, in order to obtain absolute numbers of estimated extraction of construction minerals.

Trade data

Trade data include raw materials and goods produced out of:

1. Fossil fuels: petroleum, natural gas and coal, including peat
2. Minerals: ferrous and non-ferrous metal minerals, non-metal industrial and non-metal construction minerals
3. Biomass: biomass of crop, forest or animal origin and residues/animal food
4. Other: products and product groups to whom the allocation to one or the other material group is not or hardly possible.

General aspects: In order to generate the data set for UNEP database, the methodology described by Eurostat (2013[15]) was used if not otherwise indicated below.

Currently, United Nations Comtrade is the only source which globally collects original trade data of a large number of countries with a wide range of years and a high differentiation of products and product groups. Thus, United Nations Comtrade is used as the basic source in the present database. However, there are some restrictions and limitations which are solved as described below.

One general restriction is that the physical dimension of trade flows is not reported completely; depending on the year, around 10 to 20% of all trade flows reported are not reported in the dimension of their mass. In order to overcome this restriction, the gap-filling method as described in Dittrich (2010[16]) and Dittrich/Bringezu (2010[17]) was applied: All missing mass values in United Nations Comtrade were filled using the global annual price for each commodity group, starting at the most differentiated level, then summed up according to the classification structure and repeated at the next higher differentiation level up to the total sum.

A second restriction is incompleteness in country coverage and a third restriction is implausible data, particularly regarding trade in natural gas and petroleum. In the following, the main steps to overcome the two last mentioned restrictions are described for each of the material categories.

Fossil fuels

Global data on trade in fossil fuels are provided by United Nations Comtrade and by IEA. However, the coverage of both data sources is not complete in terms of countries, years and products. While IEA shows better coverage and higher data quality regarding countries with large and medium trade flows of raw fossil fuels, the coverage regarding countries with small trade flows is better in United Nations Comtrade. Trade in further processed goods out of fossil fuels (such as products out of plastics) is covered only by United Nations Comtrade. Thus, taking advantage of both sources, data regarding products and data of countries with small trade flows (not covered by IEA at all) were fully taken from United Nations Comtrade. IEA data were used to check, complement and/or replace United Nations Comtrade data as described in the following.

All aggregated data on natural gas, petroleum and coal in the definition of IEA were calculated using the United Nations Comtrade database and compared with IEA data, treated in the way as described in the section on extraction above. Separated for natural gas, petroleum and coal, the criteria of coverage in time, plausibility of data, and the perceived reliability of the reporter were applied to decide which of the basic sources to use. Regarding trade in coal, in the majority of cases the comparison

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[15] http://ec.europa.eu/eurostat/documents/1798247/6191533/2013-EW-MFA-Guide-10Sep2013.pdf/54087dfb-1fb0-40f2-b1e4-64ed22ae3f4c

[16] Dittrich, M. 2010. Physische Handelsbilanzen. Verlagert der Norden Umweltbelastungen in den Süden? Kölner Geographische Arbeiten, 91. Köln.

[17] Dittrich, M. and S. Bringezu. 2010. The physical dimension of international trade. Part I: Direct global flows between 1962 and 2005. Ecological Economics 69: 1838–1847.

did not show significant differences thus the data with the higher coverage in time were taken. Regarding trade in natural gas and petroleum, in the majority of cases, data from IEA were taken to replace United Nations Comtrade data as they show wider time coverage and more plausible values.

In addition to the methodology described by Eurostat and taking advantage of the fact that physical values for all differentiated product groups are available, all products created from fossil fuels (e.g. furniture or cloth made from plastics) were allocated as far as possible to the different subcategories according to their dominant input materials.

Metal and non-metal minerals

United Nations Comtrade was taken as the basic source, including the gap-filling method as described above.

Implausible data were corrected using bilateral data provided by United Nations Comtrade and taking the quality of the reporting countries into account. In few cases, checks with data from geological services were also done.

Additional to the methodology described by Eurostat (2011) and taking advantage of the fact that physical values for all differentiated product groups are available, the products out of metals and non-metal minerals were allocated to the subcategories ferrous, non-ferrous, industrial and construction minerals. For example, nails, wires or structural elements made of aluminium, copper or batteries were allocated accordingly to the subgroup “non-ferrous” while nails, wires etc. made of iron or steel were allocated to the subgroup “ferrous”.

The differentiation of non-metal minerals into the subgroups industrial and construction minerals is still not sufficiently solved in the Eurostat guidelines due to the fact that several minerals are used for both purposes. In future, further discussion and convention are required.

Biomass

Global trade data on biomass are provided by United Nations Comtrade and FAO. Country coverage is higher in FAO while coverage of products made from biomass (e.g. cloth or furniture) is higher in United Nations Comtrade. The decision was made to take advantage of both databases, using United Nations Comtrade as the basic one and using FAO to check, complement or replace data generated from United Nations Comtrade for two main reasons: first, using only one database as the basic source for all material categories in trade minimizes inconsistencies regarding completeness of biomass products; second, United Nations Comtrade collects original data from countries while FAO data are partly treated or estimated based on a methodology which is not always reproducible transparently. The following steps were implemented in order to check, complete or replace United Nations Comtrade data on biomass.

At the level of the subgroups, the aggregated data based on both data sources were compared. Data from FAO were aggregated according to the methodology explained by Eurostat, however, some differences and improvements need to be specified:

- Some forest products (e.g. some chipboards) are not classified by type (out of coniferous or non-coniferous wood) in FAO database. The Eurostat manual does not explain this clearly. In this database, it was assumed that half of the unspecified forest product group is of coniferous and the other half is of non-coniferous species.
- Living animals, counted in heads, were converted using country-specific conversion factors as documented by FAO[18].

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[18] http://www.fao.org/fileadmin/templates/ess/documents/methodology/tcf.pdf

In the majority of the cases, the two databases did not show significant differences. Thus, incomplete time periods for countries in United Nations Comtrade were completed using FAO sources. In cases where the covered time period was very fragmented in United Nations Comtrade, the full data set was taken from FAO. Due to the fact that coverage of products in United Nations Comtrade is higher, the data generated from United Nations Comtrade includes a higher variety of products (such as cloth, furniture or chemicals made of biomass) than the data sets for which FAO was taken as the source.

Other products

In order to improve the allocation methodology in the present UNEP material flow database it was aimed to minimize the category “other”. Therefore, as far as possible all traded products and product groups, at the most differentiated level possible, were allocated to subgroups according to their main input materials. For example: furniture made of steel was allocated to the subgroup “ferrous metals” while furniture made of wood was allocated to the subgroup “forest origin”. In this way, the allocation was particularly improved for chemicals and related products, and for manufactured and miscellaneous products and articles.

As a result, the group “other” now includes only product groups without any information on materials, such as antiques, and product groups made of materials which cannot be attributed to any material group, e.g. oxygen or (bottled) drinking water.

MRIO frameworks

The Eora MRIO database

In recent years, global multi-regional input-output (MRIO) analysis has become an important tool to analyse and understand global economic, environmental and social impacts associated with economic activities such as purchasing goods and services or exporting and importing raw materials. Global MRIO analysis is potentially able to identify billions of global supply chains and to quantify the impacts that occur in every step of these supply chains.

MRIO analysis broadly consists of three elements:

a) A set of global MRIO tables

b) A set of matching environmental data tables (so-called “satellite accounts”)

c) A mathematical framework to query these two data sets for global impact analysis.

The foundations the mathematical framework for global MRIO analysis were laid by Nobel Laureate Wassily Leontief, who conceived the basic concepts of MRIO analysis in the 1930s (Leontief 1936). The size and the level of detail of the underlying MRIO tables and satellite accounts determine the accuracy of the results and the applicability of MRIO analysis in a global setting. For reliable global supply analyses, global MRIO tables with high country- and sector resolutions are indispensable.

MRIO tables contain transaction values of traded goods and services between pairs of economic sectors. In order to compile these tables, large amounts of data must be considered and processed. In the case of a global MRIO table, large amounts of data from different sources must be merged into a single table. These source data sets often contain conflicting information, and the task of reconciling these large amounts of misaligned, conflicting and disparate data cannot be achieved using established methods for MRIO compilation.

Over recent years, a handful of academic research collaborations have been formed to overcome these shortcomings and construct databases of highly detailed global MRIO tables. Among these databases the Eora database (Lenzen et al. 2012 and Lenzen et al. 2013) offers the highest level of detail and most expansive country coverage.

The Eora database is a time series of global MRIO tables. The key features of Eora are:

- Continuous yearly time series from 1990 to 2012. The time series is currently being extended backward to 1970 and forward to 2014
- Representation of 189 individual countries plus one "Rest of the World" region
- The sectoral detail ranges from 25 to 501 sectors per country
- The total number of sectors in the Eora tables exceeds 15,000
- Five valuation sheets for each year of the time series
- Fully aligned satellite block for all years of the time series
- Eora is the only global MRIO database in existence that comes with reliability information for every data point
- Eora is freely available for academic use under worldmrio.com.

During the construction of Eora (described in detail in Lenzen et al. 2013), a number of key advantages in the field of MRIO table compilation were achieved. Firstly, as much official statistical data was included in the construction process as possible. These data included official national input-output tables, which are published by national statistical agencies, and international trade data, which was sourced from the United Nations Commodity Trade database and other international databases. In some cases, for example for the countries of the European Union, additional trade data were available from other statistical agencies such as Eurostat.

Secondly, the reliability of each source data point was considered during the reconciliation process, and information on the reliability of each data point of the final MRIOs was provided.

Thirdly, a mathematical framework was developed that allowed for the consideration of all available source data (including their reliability information) during the MRIO compilation process. This ensured that all available raw data sets are accurately represented within the Eora database. In cases where data sourced from different raw data sets presented misaligned, disparate and conflicting information, the reconciliation algorithm aimed for a 'best-fit' solution. This solution ensured that – in case of conflicting information from different source data sets – the final Eora MRIO tables adhere to all source data sets as well as possible. The reliability data for the source data points was considered during this process, meaning that in case of a conflict, more reliable source data are more strictly adhered to compared to less reliable source data. Using the methodology presented by Lenzen, Wood and Wiedmann (2010), reliability information was calculated for each data point of the Eora database. This ensures a high level of data quality and ultimately high reliability of the final Eora MRIO tables.

Finally, Eora is the first MRIO database that was compiled using high-performance computing facilities. The mathematical challenges during the compilation process were mathematically expressed as a large-scale constrained optimization problem. The size and complexity of this problem required computing capabilities far beyond of those offered by off-the-shelf computing systems. Eora was compiled on a custom-built high-performance computing cluster with a total of 40+ cores and 400 GB of RAM. The total amount of data processed to obtain the Eora MRIO tables for a single year reached as high as 80 GB. The complete Eora time series exceeds 700 GB in data.

During the construction of Eora, a strong focus was placed on the application of Eora on global environmental impact assessment. To account for this usage profile, Eora was constructed with the extensive satellite block containing a large number of environmental indicators such as GHG emissions, land use, water use and energy use.

Eora is reviewed an extended annually to ensure the timeliness of the database and the availability of data for recent years.

The GTAP 8 MRIO database

The calculations of material footprints with GTAP were performed with GTAP version 8, which features 129 regions and 57 sectors (Narayanan, Badri and McDougall 2012). Twenty of the 129 regions included in GTAP 8 are estimates of aggregated world regions. GTAP does not explicitly publish a harmonized MRIO table. The original background of the GTAP database was computable general equilibrium analysis of trade policies. However, an MRIO table can easily be constructed from the tables published (Peters, Andrew and Lennox 2011). As a consequence, GTAP has been used for several environmental assessments, in particular related to GHG emissions (Peters and Hertwich 2008, Wiedmann 2009). The GTAP project is based at Purdue University where global trade databases have been compiled since 1993. Country-specific input-output tables are submitted by voluntary contributors following guidelines on definitions and sector classification. The tables are checked by GTAP for inconsistencies and, when necessary, disaggregated to the 57 sector level. This is followed by a balancing procedure with trade data stemming from the United Nations Comtrade and the United Nations Service trade data set (Tukker and Dietzenbacher 2013). From a conceptual point of view, a disadvantage of GTAP is the fact that the GTAP data set is a mixture of national IOTs classified industry-by-industry and product-by-product, however modellers tend to handle the MRIO system as a product-by-product model. GTAP has an ever-increasing level of regional detail and a moderate level of sectors. The sector classification differentiates 12 agricultural activities, hence setting a particular focus on issues related to agriculture and biomass use. However, GTAP only contains one sector of mining of abiotic raw materials, which is a severe limitation for the calculation of material footprints, as a very large number of different commodities are allocated to just one sector (see Table 18 below). In GTAP 8, 2007 is the most recent reference year.

EXIOBASE 2.2

The EXIOBASE database was developed in several European research projects (EXIOPOL, CREEA, DESIRE) and particularly designed for environment-related applications. National IO tables serve as the basic data source and starting point for further disaggregation, in order to represent and differentiate crucial sectors with environmentally-sensitive activities (Wood et al. 2015). EXIOBASE version 2.2 distinguishes 200 products (and 163 industries), of which 33 products refer to extraction of biotic and abiotic raw materials (Tukker et al. 2013). EXIOBASE is thus the database with the highest level of detail for calculations of material footprints. Another advantage, when compared to GTAP 8, is the availability of supply and use tables as well as symmetric industry-by-industry and product-by-product tables for the whole harmonized MRIO system. In terms of regional detail, the model has a clear focus on the EU. The EU-27 and its 16 most important trading partners are explicitly modelled in EXIOBASE 2.2, representing about 95% of global GDP (Wood et al. 2015). The rest of the world is aggregated into five separate rest-of-world regions. All in all, version 2.2 comprises 48 regions and countries. The EXIOBASE 2.2 reference year is 2007. A first time series will be made available with the upcoming EXIOBASE 3.

Table 18. Concordance tables between material satellite data and sector in EXIOBASE and GTAP

No.	Material satellites	EXIOBASE Code	EXIOBASE Name	GTAP Code	GTAP Name
1	Paddy rice	p01.a	Rice	1 / PDR	Paddy rice
2	Wheat	p01.b	Wheat	2 / WHT	Wheat
3	Cereals n.e.c.	p01.c	Cereal grains n.e.c.	3 / GRO	Cereal grains n.e.c.
4	Roots and tubers	p01.d	Vegetables, fruit, nuts	4 / V_F	Vegetables, fruit, nuts
5	Sugar crops	p01.f	Sugar cane, sugar beet	6 / C_B	Sugar cane, sugar beet
6	Pulses	p01.d	Vegetables, fruit, nuts	4 / V_F	Vegetables, fruit, nuts
7	Nuts	p01.d	Vegetables, fruit, nuts	4 / V_F	Vegetables, fruit, nuts
8	Oil bearing crops	p01.e	Oil seeds	5 / OSD	Oil seeds
9	Vegetables	p01.d	Vegetables, fruit, nuts	4 / V_F	Vegetables, fruit, nuts
10	Fruits	p01.d	Vegetables, fruit, nuts	4 / V_F	Vegetables, fruit, nuts
11	Fibres	p01.g	Plant-based fibres	7 / PFB	Plant-based fibres
12	Other crops	p01.h	Crops n.e.c.	8 / OCR	Crops n.e.c.
13	Crop residues (used)	p01.i	Cattle	9 / CTL	Bovine cattle, sheep and goats, horses
		p01.j	Pigs	10 / OAP	Animal products n.e.c.
		p01.k	Poultry	11 / RMK	Raw milk
		p01.l	Meat animals n.e.c.	-	-
		p01.n	Raw milk	-	-
14	Fodder crops	p01.i	Cattle	9 / CTL	Bovine cattle, sheep and goats, horses
		p01.j	Pigs	10 / OAP	Animal products n.e.c.
		p01.k	Poultry	11 / RMK	Raw milk
		p01.l	Meat animals n.e.c.	-	-
		p01.n	Raw milk	-	-
15	Grazed biomass	p01.i	Cattle	9 / CTL	Bovine cattle, sheep and goats, horses
		p01.l	Meat animals n.e.c.	11 / RMK	Raw milk
		p01.n	Raw milk	-	-
16	Timber (Industrial roundwood)	p02	Products of forestry, logging and related services	13 / FRS	Forestry

No.	Material satellites	EXIOBASE Code	EXIOBASE Name	GTAP Code	GTAP Name
17	Wood fuel and other extraction	p02	Products of forestry, logging and related services	13 / FRS	Forestry
18	Wild fish catch	p05	Fish and other fishing products; services incidental of fishing	14 / FSH	Fishing
19	Iron Ores	p13.1	Iron ores	18 / OMN	Minerals n.e.c.
20	Copper ores – gross ore	p13.20.11	Copper ores and concentrates	18 / OMN	Minerals n.e.c.
21	Nickel ores – gross ore	p13.20.12	Nickel ores and concentrates	18 / OMN	Minerals n.e.c.
22	Lead ores – gross ore	p13.20.15	Lead, zinc and tin ores and concentrates	18 / OMN	Minerals n.e.c.
23	Zinc ores – gross ore	p13.20.15	Lead, zinc and tin ores and concentrates	18 / OMN	Minerals n.e.c.
24	Tin ores – gross ore	p13.20.15	Lead, zinc and tin ores and concentrates	18 / OMN	Minerals n.e.c.
25	Gold, silver, platinum and other precious metal ores – gross ore	p13.20.14	Precious metal ores and concentrates	18 / OMN	Minerals n.e.c.
26	Bauxite and other aluminium ores – gross ore	p13.20.13	Aluminium ores and concentrates	18 / OMN	Minerals n.e.c.
27	Uranium and thorium ores – gross ore	p12	Uranium and thorium ores	18 / OMN	Minerals n.e.c.
28	Other metal ores – gross ore	p13.20.16	Other non-ferrous metal ores and concentrates	18 / OMN	Minerals n.e.c.
29	Chemical and fertilizer minerals	p14.3	Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	18 / OMN	Minerals n.e.c.
30	Salt	p14.3	Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	18 / OMN	Minerals n.e.c.
31	Clays and kaolin	p14.2	Sand and clay	18 / OMN	Minerals n.e.c.
32	Non-metallic minerals – primarily construction	p14.1	Stone	18 / OMN	Minerals n.e.c.

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About the International Resource Panel

This report was prepared for the International Resource Panel (IRP). The IRP was established to provide independent, coherent and authoritative scientific assessments on the use of natural resources and its environmental impacts over the full life cycle and contribute to a better understanding of how to decouple economic growth from environmental degradation. Benefiting from the broad support of governments and scientific communities, the Panel is constituted of eminent scientists and experts from all parts of the world, bringing their multidisciplinary expertise to address resource management issues. The information contained in the International Resource Panel's reports is intended to be evidence based and policy relevant, informing policy framing and development and supporting evaluation and monitoring of policy effectiveness. The Secretariat is hosted by the United Nations Environment Programme (UNEP).

Since the International Resource Panel's launch in 2007, fifteen assessments have been published. This first series of reports covered biofuels; priority economic sectors and materials for sustainable resource management; metals stocks in society, their environmental risks and challenges, their rates of recycling and recycling opportunities; water accounting; city-level decoupling and finally the untapped potential for decoupling resource use and related environmental impacts from economic growth.

The assessments of the IRP to date demonstrate the numerous opportunities for governments and businesses to work together to create and implement policies to encourage sustainable resource management, including through better planning, more investment, technological innovation and strategic incentives. Following its establishment, the Panel first devoted much of its research to issues related to the use, stocks and scarcities of individual resources, as well as to the development and application of the perspective of 'decoupling' economic growth from natural resource use and environmental degradation. Building upon this knowledge base, the Panel has now begun to examine systematic approaches to resource use. These include the direct and indirect (or embedded) impacts of trade on natural resource use and flows, and the city as a societal 'node' in which much of the current unsustainable usage of natural resources is socially and institutionally embedded. In a similar vein it has become apparent that the resource use and requirements of the global food consumption call for a better understanding of the food system as a whole, and in particular its role as a node for resources such as water, land, and biotic resources on the one hand and the varied range of social practices that drive the consumption of food on the other. The years to come will therefore focus on and further deepen these work streams.

About the UNEP Division of Technology, Industry and Economics

The UNEP Division of Technology, Industry and Economics (DTIE) helps governments, local authorities and decision-makers in business and industry to develop and implement policies and practices focusing on sustainable development.

The Division works to promote:

- sustainable consumption and production,
- the efficient use of renewable energy,
- adequate management of chemicals,
- the integration of environmental costs in development policies.

The Office of the Director, located in Paris, coordinates activities through:

- **The International Environmental Technology Centre** - IETC (Osaka, Shiga), which implements integrated waste, water and disaster management programmes, focusing in particular on Asia.
- **Production and Consumption** (Paris), which promotes sustainable consumption and production patterns as a contribution to human development through global markets.
- **Chemicals** (Geneva), which catalyzes global actions to bring about the sound management of chemicals and the improvement of chemical safety worldwide.
- **Energy** (Paris), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.
- **OzonAction** (Paris), which supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.
- **Economics and Trade** (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies.

UNEP DTIE activities focus on raising awareness, improving the transfer of knowledge and information, fostering technological cooperation and partnerships, and implementing international conventions and agreements.

For more information,
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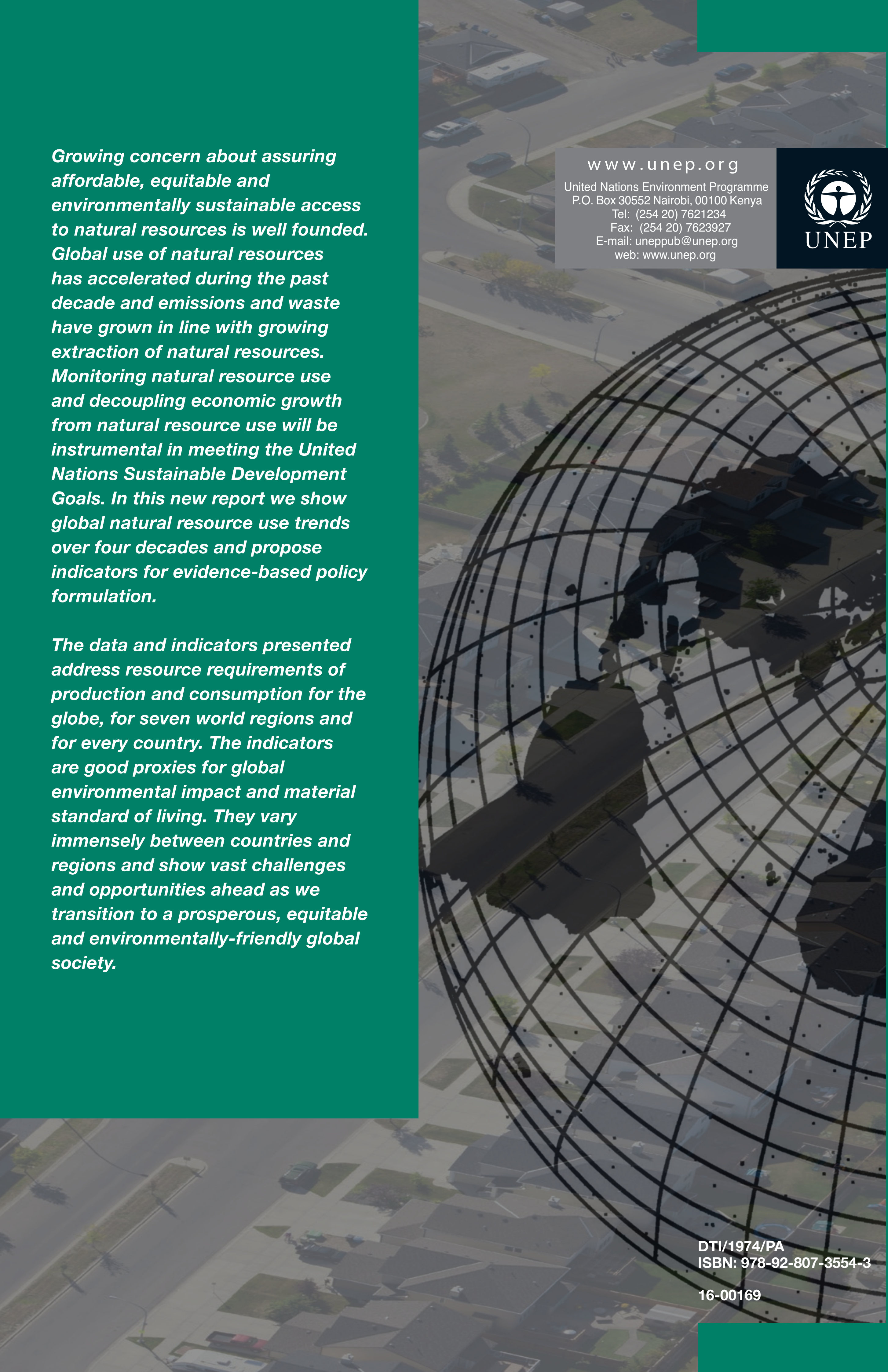
Growing concern about assuring affordable, equitable and environmentally sustainable access to natural resources is well founded. Global use of natural resources has accelerated during the past decade and emissions and waste have grown in line with growing extraction of natural resources. Monitoring natural resource use and decoupling economic growth from natural resource use will be instrumental in meeting the United Nations Sustainable Development Goals. In this new report we show global natural resource use trends over four decades and propose indicators for evidence-based policy formulation.

The data and indicators presented address resource requirements of production and consumption for the globe, for seven world regions and for every country. The indicators are good proxies for global environmental impact and material standard of living. They vary immensely between countries and regions and show vast challenges and opportunities ahead as we transition to a prosperous, equitable and environmentally-friendly global society.



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