Session 3.

A Sustainable Baltic Region

Man and Materials flows

Towards sustainable materials management

Editor and main author
Sten Karlsson
Chalmers University of Technology
and Göteborg University

A Sustainable Baltic Region

A SERIES OF BOOKLETS FROM
THE BALTIC UNIVERSITY PROGRAMME

1. The Road towards Sustainability
A historical perspective
Editor Sverker Sörlin, Umeå University

2. Energy
From fossil fuels to sustainable energy resources
Editor Jürgen Salay, Stockholm Environment Institute and Lund University

3. Man and Materials Flows
Towards sustainable materials management
Editor and main author Sten Karlsson, Chalmers University of Technology and Göteborg University

4. Food and Fibres
Sustainable agriculture and forestry
Editors Sten Ebbersten and Bengt Bodin,
Swedish University of Agricultural Sciences

5. Sustainable Industrial Production
Waste minimization, cleaner technology and industrial ecology
Editor Joseph Strahl, Lund University

6. Towards Sustainable Mobility
Transporting people and goods in the Baltic Region
Editors Emin Tengström, Aalborg University
and Marie Thynell, Göteborg University

7. Cities and Communities
The development of sustainable habitation
Editor Harri Andersson, University of Turku

8. Ecological Economics
Markets, prices and budgets in a sustainable society
Editor Tomasz Zylicz, University of Warsaw

9. The Foundations of Sustainable Development
Ethics, law, culture and the physical boundaries
Editor Lars Rydén, Uppsala University

10. From Intention To Action
Implementing sustainable development
Editor and main author Magnus Andersson, Vrije Universiteit, Amsterdam

The series of booklets are available at the Baltic University Centres
and at the Coordination Secretariat att Uppsala University.

Uppsala University, The Baltic University Programme Coordination Secretariat,
Box 2109, S-75002 Uppsala, Sweden

Baltic University Programme Centres

Sweden; Umeå University, Centre for Interdisciplinary Studies, 901 87 Umeå, Sweden. Tel +46-90-16 55 87 Fax -16 66 84; **Finland**: Centre for Continuing Education, Åbo Akademi, Biskopsgatan 10, SF-20 500 Turku. Tel +358-2-265 41 25 Fax -265 49 43; **Estonia**: Tallinn Technical University, Dept of Economics, Ehitajatee 5, EE-0026 Tallinn. Tel 372-2-47 43 42 Fax -53 24 46; **Latvia**: Latvian University, Centre for Env. Studies, K. Valdemara 48 LV-1013 Riga. +371-2-36 60 19 Fax +371-7-22 50 39; **Lithuania**: Kaunas University of Technology, Dept of Env. Engineering, Radvilenu 19, LT-3028 Kaunas. +370-7-75 10 16 Fax -75 60 63; **North Western Russia**: St Petersburg University, Dept of Int. Baltic and Arctic Projects, 10th Line 33/35, 199 178 St Petersburg. Tel +7-812-218 97 09 Fax -218 13 46; **Kaliningrad district**: Kaliningrad State University, Dept of Geography, A. Nevsky 14, 236 041 Kaliningrad. +7-0112-43 24 34 Fax -46 58 13; **Belarus**: Belarusan Polytechnical Academy, Dept of Ecology, Skaryna Av. 65, 220 027 Mensk+375-172-39 91 29 Fax -31 30 49; **Ukraine**: L'viv State University, Faculty of Int. Relations, 1 Universytetska Str. 290 000 L'viv. +380-322-72 79 73 Fax -72 79 81; **Poland**: Dept of Int. Relations, University of Gdansk, ul. Budzisza 4, 81 712 Gdansk. +48-58-51 44 55 Fax -57 06 75; **Germany**: University of Lüneburg, Dept of Env. Science, Postfach 2440, D-21332 Lüneburg. +49-4131-71 43 41 Fax -71 41 06; **Denmark**: University of Copenhagen, Institute of Political Science, Rosenborggade 15, DK-1130 København. +45-35-32 34 04 Fax -32 33 99.

3

MAN AND MATERIALS FLOWS

Towards sustainable materials management

Authors
Sten Karlsson
Christian Azar
Göran Berndes
John Holmberg
Kristian Lindgren

Editor and main author
Sten Karlsson
Institute of Physical Resource Theory
Chalmers University of Technology and Göteborg University
S-412 96 Göteborg, Sweden
Tel: +46 31 772 31 49, Fax: +46 31 772 31 50
E-mail frtsk@fy.chalmers.se

Series editor: Lars Rydén, Uppsala University
English editor: Ann Crossley
Illustrations: Karin Hallgren
Photo: Inga-Maj Lehman

Main financer: The Swedish Institute
Production: Uppsala Publishing House
Printed by: Ditt Tryckeri, Uppsala 1997
First edition, January 1997

ISBN 91-7005-126-7

Project coordination: The Baltic University Secretariat
Uppsala University, Box 2109, S-750 02 Uppsala, Sweden

PREFACE

The text in this book presents various system aspects on materials flows in society and nature and then mainly from a natural sciences and technical point of view. It is aiming at giving an overview of important material flows in society and in nature and their interactions in a sustainability perspective and the text is therefore of a more principal character. More examples and applications in specific sectors of society can be found in the other books of this series. Unfortunately, the examples and data presented in this book are exclusively from western countries. The documented and available studies on materials flows in the society and their connections to the environmental and resource problems are to an overwhelming majority describing western societies and this book has drawn from these studies.

Several persons at our department have contributed to this book. Chapter 5 on the carbon flow is written by Christian Azar and Göran Berndes. John Holmberg has contributed to various parts of chapter 2, 4 and 7, and Kristian Lindgren to chapter 4. Karl-Erik Eriksson and Kristian Lindgren have reviewed the manuscript at various stages. Valuable contributions and editing have been performed by Lars Rydén at the Baltic University.

The writing of this book has not been possible to fully finance within the limited budget of the course ”A Sustainable Baltic Region”, but has in practice partly been a part of the project ”Physically consistent scenarios for a future sustainable Sweden” ongoing at our institute and supported by the Swedish Environ-mental Protection Agency. This support is fully acknowledged.

Göteborg, November 1996

Sten Karlsson
Institute of Physical Resource Theory
Chalmers University of Technology and Göteborg University

CONTENTS

The old practice of building wooden multi-storeyed houses was outlawed in many countries last century to prevent devastating fires in city centres. Contemporary fire-prevention techniques however have made this problem obsolete. In Sweden wooden houses have been legal again since 1994. Four- and five-storey apartment houses with wooden frames are today being built in e.g. Linköping (as seen in this picture) by Skanska, one of the largest construction companies in the region.

Wooden multi-storeyed apartment houses constitutes a dramatic case of dematerialised design. Wood is much lighter than the conventional concrete. Per apartment the weight is about 25 tonnes for wood and 100 tonnes for concrete. The construction requires less ground preparation, smaller cranes, and is easier and faster. As a consequence, the houses are potentially much cheaper. In addition, direct environmental gains are considerable. For the transport of material to the construction site, for example, smaller trucks can be used with diminishing emissions and less wear on roads. As will be clear from this booklet, the immense use of cement contributes to green-house carbon dioxide while wood is a renewable resource easily accessible in the Baltic region.

Wood house-building techniques are being developed today in an inter-Nordic project with the participation of Finland, Denmark, Norway and Sweden, with a centre at Lund University of Technology. (Photo: Holger Staffansson)

1.

MAN AND MATERIALS FLOWS

1.1 A question of what and of how much

For his survival and pleasure man is using all kinds of mat-erial from the surrounding world: for food, for shelter, for transport and all other needs and demands in everyday life. Obviously, in a 'natural state', the amounts needed were comparatively small and did not require any large chunks to be taken out of nature. This retrieval of natural resources did not lead to any harmful impacts nor did the waste, when returned to the surrounding nature, cause any harm. The turnover of materials caused by man were minor and well integrated parts of the natural flows.

This harmonious state of affairs has long since changed completely. The use of natural resources and materials is today different both quantitatively and qualitatively. The impact is not only environmental effects from pollution, waste and the like. There is also the other end of the process — the extraction of materials from nature. We mine scarce and exhaustible resources and harvest extensively from more or less man-made ecosystems in agriculture and forestry, interfering with natural habitats and ecosystems.

When travelling through any part of our region, it is easy to perceive the enormous quantitative increase of materials turnover caused by man. The large infrastructures – cities, villages, roads, bridges, mines, reservoirs, etc. – bear witness to the overwhelming impact of man's resources use. In fact, this materials turnover today amounts to over 60 tonnes per year and per capita according to a recent estimate of the German situation. (This figure does not take into account the use or diversion of water, which alone is close to 900 tonnes per year and per capita.)

The question is of course whether this extensive materials use can continue in the long term. Is it sustainable? The answer is clearly no. However, it is not easy to say exactly what a sustainable materials intensity would be. Later in this booklet we shall address this question. However, without a doubt, we need to diminish our resources use drastically. Figures between a factor of four and of ten have been suggested.

There is also an important qualitative dimension here. Materials that were never touched in the more 'natural societies' are now in daily use. These include heavy metals that have been retrieved from their ores, and are in circulation in societies and man-made chemical compounds that are harmful and toxic. They also includes chemicals that are not at all or are very slowly broken down in biological processes. Again, this aspect of present-day materials turnover is not sustainable. Again we need to reconsider all processes where such materials occur to change them into non-polluting and sustainable procedures.

Table 1.1 Some human disturbances of natural flows and ecosystems (terminology is explained in chapter 2).

	Human disturbance relative to natural levels	*System character of the disturbance*
Carbon (C)	+ 30 % in the atmospheric stock	lithosphere to ecosphere
Nitrogen (N)	+ 200–300 % in the nitrogen fixation	1) inert to active N in ecosphere 2) lithosphere to ecosphere
Sulphur (S)	+ 1,000 % in the flow of reduced S to the atmosphere	lithosphere to ecosphere
Metals	up to 2,400% in the flow from the lithosphere	lithosphere to technosphere (eventually ecosphere)
Persistent/ artificial compounds	very large increases in the flow to the ecosphere	technosphere to ecosphere
Terrestrial ecosystems	40 % appropriation of the terrestrial net primary production	ecosystems disruption, threat to biodiversity

1.2 Disturbances of the natural materials cycles

The influence of man on materials turnover may be compared to natural cycles to assess their relative importance (see Table 1.1). The turnover of carbon, nitrogen, water, oxygen, etc. has been studied closely and the natural flows and their most important component subflows are known. Let us briefly review some basic facts.

Nitrogen is the major component of our atmosphere due to its 80 per cent content of nitrogen gas. It is also a major component of all living cells. The flow between these two pools of nitrogen is, on the other hand, rather small. Nitrogen is naturally retrieved from the atmosphere mainly through the activities of certain so-called nitrogen-fixing bacteria. Because of this limited supply, nitrogen is often a limiting nutrient in agriculture and other ecosystems. The invention of industrial nitrogen fixation, which made artificial nitrogen fertilizers possible, changed this situation dramatically and the nitrogen flow to the biosphere has almost doubled due to this activity.

The result is accumulation of nitrogen in natural ecosystems such as water and, in particular ultimate recipients such as the Baltic Sea, resulting in excessive eutrophication, algal growth and dead seabeds. In all this picture adds up to a manipulation of the natural nitrogen cycle by man on a major scale.

A similar story can be told about carbon. Carbon is present in the atmosphere as carbon dioxide, a minor component accounting for only 0.036 per cent. Again, it is a key component in all living cells. In the flows between the biosphere and the atmosphere, key processes are carbon dioxide fixation, carried out by green plants through photosynthesis, and combustion, either by the burning of biomass or by respiration by living organisms. When these two processes are balanced the carbon dioxide level in the atmosphere is constant. However, the large-scale societal use of fossil fuels for energy production has upset this balance seriously. A constant increase of carbon dioxide levels in the atmosphere, now amounting to about 130 per cent of natural levels, has been the result. Again, a manipulation of the natural cycles has led to an increasingly more threatening situation with serious environmental consequences.

The nitrogen and carbon cycles represent the best-known and serious changes in natural cycles caused by man. But this is only the beginning, rather than the end. Similar stories can be told for phosphorus, for sulphur and, obviously, for a number of the metals and chemical compounds in use in society. For instance, all the heavy metals are more or less toxic and their continued mining results in an ongoing accumulation in societies. Of course, materials turnover in our societies needs a fundamental re-evaluation. The situation is not sustainable and major changes are needed.

1.3 The need for a system perspective

Since the environmental problems of modern industrial society were put on the agenda in the sixties, attention has been paid to many environmental and resources problems and various counter measures and adaptations have successively been introduced. However, meanwhile the character (or at least the perceived character) of the environmental problems has changed. We can here point to four important such trends (see Figure 1.1).

(i) *From local to global:*
The scope of environmental issues has proceeded to an even greater geographical scale and today global environmental issues often dominate the environmental discussion. Many of the earliest local pollution problems around industries have been solved by building higher chimneys and longer discharge pipes. But this ”philosophy of dilution” only transferred local problems, with some delay, into regional problems or even global concerns. For example, the burning of fossil fuels, which was noticed as the cause of local smog problems in London in the fifties, appeared as regional acidification problems in Scandinavia in the seventies. Now in the nineties it has turned into a global issue due to the emission of carbon dioxide contributing to climate change.

(ii) *From specific to diffuse*:
In the fifties the activities that caused environmental problems often were distinguishable specific sources, like factory chimneys, discharge pipes, etc. Substances that used to go out through these chimneys and pipes are today often collected in filter devices. These filters cause diffuse discharges when they are deposited. Furthermore, today, diffuse emissions from the consumption sector dominate over the specific emissions from the production sector for many substances. Bergbäck [1992] shows that this is the case for chromium and cadmium in Sweden since 1970 and 1975, respectively.

(iii) *From short delay to long delay*.
The fact that many substances are embedded in filters, etc. from production processes as well as in products, also implies that there is a longer delay before we can recognize damage in nature. For substances that are captured in a filter from a purifying plant, it can

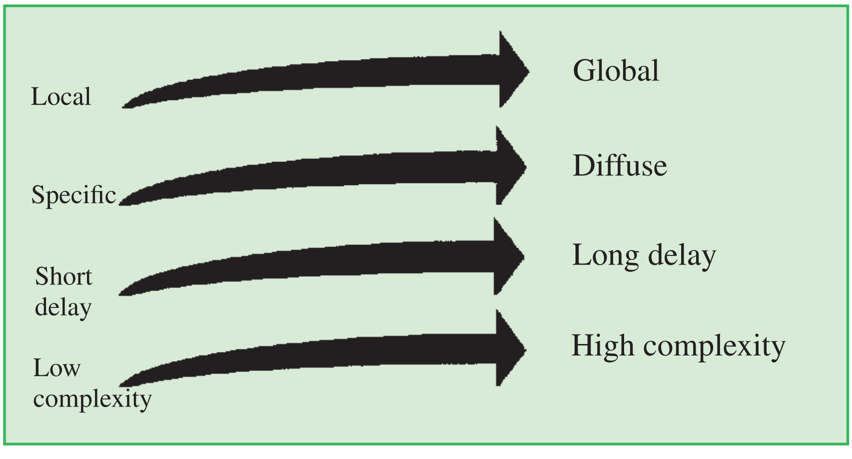


Figure 1.1 The changing character of the environmental problems [from Holmberg & Karlsson 1992].

take several hundreds of years from the time the filter is deposited until the substances reach ground water. This means that, for many substances, the annual emission only constitutes a small amount of the large accumulation within the techno-sphere and in waste deposits.

(iv) *From low complexity to high complexity:*
The causal chains of environmental problems have become more complex. Today, many different activities cause many different environmental problems in many different ways. The historical societal influence on nature was often characterized by quite simple causal chains such as a dead lake poisoned by a nearby factory. Today the causal chains in the societal influence on nature look more like a web. In many cases they also go deeper into the societal turnover of energy and materials. For instance, once again, the smog problem was due to the specific way of burning coal. However, acidification is due to a component in the fuel, the sulphur. Now, we begin to realize that fossil fuels themselves are the problem.

The changing character of the environmental problems, described above, implies that we cannot use our senses to detect whether society's influence on nature is sustainable and that the solutions to the problems will involve not only marginal but larger and more radical adaptations of the industrial turnover of energy and materials. There is a growing awareness of the limited capacity of the Earth as a resource system for supporting a growing population with an intensive exchange of materials and energy with the environment. The concept of sustainable development has recently emerged and, especially since the Brundtland report was published [WCED 1987], has become an essential ingredient in many discussions on resources and environmental management strategies.

However, society is considerably undecided about the implementation and materialization of strategies for a sustainable society. This is partly due to lack of knowledge, both about what the environmental restrictions really are and what opportunities society has to change its course, and, not least, a lack of understanding about what a sustainable society might look like, while fulfilling vital needs and wishes.

The law of mass conservation

In modern physics, mass is a form of energy according to Einstein's famous formula E = mc2. However, outside very specific areas, this has no significance for everyday life in modern society.

If we disregard nuclear reactions and radioactive decay, which actually are relatively unusual on the Earth's surface, the conservation also holds in a stronger form: the number of atoms/ions of a certain nuclide (a certain isotope of a certain chemical element) is conserved as well as the total number of electrons. In a system in which there are also no chemical reactions, the number of various molecules are conserved. Thus a chemical substance which is constantly emitted to the environment will remain and accumulate somewhere unless it is broken down or changed in chemical reactions. (Of course, the conservation law also holds for the degradation products.) On a still higher and societal level, for instance, various commodities are, as we already know, conserved as long as they are not destroyed.

In summary, we have concluded so far:

- the materials flows of man are large compared to nature;
- man is heavily disturbing the natural cycles of the elements and the basic prerequisites of the natural ecosystems;
- the character of the environmental problem is changing and resources and environmental problems penetrate in a complex way deep into the metabolism of the industrial society;
- the necessary adaptation is in many aspects of a fundamental character but its realization and what a sustainable society might look like are in many parts essentially unknown.

Together these circumstances and facts point to the need for a systems perspective on materials flows and the need to ask fundamental questions about the relationship between society and nature.

1.4 Matter is conserved

When applying a systems perspective to resources and environmental issues, it is natural to start with that part of physics which deals with different forms of energy and matter and conversions between them; thermodynamics. In connection with the first law of thermodynamics, the law of conservation of energy, one usually mentions the law of mass conservation. The law of mass conservation states that matter is conserved in every process. Although aspects of it have always been known scientifically it has its roots in chemistry. It was observed by Lavoisier at the end of the eighteenth century that mass was a conserved entity in chemical reactions.

However, a point to be made here is that mass conservation may hold on various levels.

The law of conservation of mass implies that, as for energy, it is possible to set up balanced accounts for various forms of matter, for example, chemical elements or even commodities, dependent on the specific circumstances for different processes. If something is changed (produced or consumed) in a certain process, conservation may hold on the next lower level, for example, the chemical elements are still conserved when a chemical substance is produced in a chemical reaction.

1.5 Flows and transformation of materials

The law of conservation of matter has some well-defined consequences when it comes to the natural turnover of materials. In a compartment of nature or society there is a certain amount, a stock, of a material. Depending on the occupied volume, the material has a certain density, concentration or grade. It is also arranged in a more or less complicated structure. Man is extracting natural materials in a raw form and transforms them into (more) valuable forms or structures to fulfil the qualities needed to perform the demanded services. There is a materials flow between forms. Often when we talk about flows of materials, we are not so interested in the movements of the materials but rather in the transformations of the materials between various forms.

Thermodynamics is heavily connected to structure and changes at the molecular/atomic level. Thus, the exergy needed in a chain of transformations is normally dominated by the chemical extraction of the valuable material from the raw materials. Modern industrial processes are in many cases quite near these limits. Further forming in manufacturing is done on a macro level with a small (theoretically required) input of exergy. On the other hand, the industrial practices in these processes are generally far from the thermodynamic limits.

The flows of conserved entities can be of two general kinds (See Fig 1.2). We can call them linear and circular flows, respectively. In a linear flow the entity is transferred from one place or form to another, which gives rise to exhaustion of the source stock and accumulation of the sink stock. On the other hand, in a circular flow there is no exhaustion and no accumulation as the materials will return to the source stock.

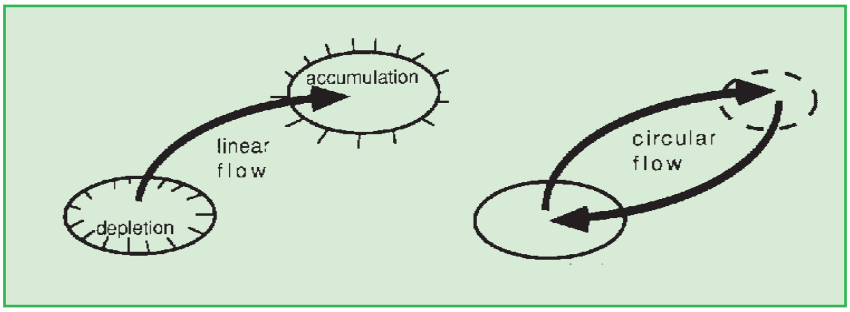


Figure 1.2 Two principal types of flow: linear and circular flows.

Many resources and environmental problems have their roots in this fundamental aspect of conservation of matter. For instance, the use of fossil fuels relies on exhaustion of relatively scarce resources of energy-rich compounds containing reduced carbon and leads to the accumulation of oxidized carbon (carbon dioxide) in the atmosphere, which ultimately changes the radiation balance and the climate on Earth.

There may be various types of by-flow connected to a main flow, that is, the intentional flow and the most valuable flow to the society, : fossil fuels contain not only useful hydrocarbons, but also, for example, sulphur, nitrogen and various heavy metals which follow the main material and are also transferred into the processes. In most manufacturing processes there are materials (for example, water, air, lubricants, cleaning agents) which are not incorporated in the final product but are still coupled to it, because they are needed to perform the processes. The materials in these flows are often lost in the waste streams.

In order to reach and extract metal ores, one needs to move and handle overburden and useless common rock. These flows are often much larger than the extracted valuable material. The building of roads and other infrastructure requires levelling and proper grounding. These activities often involve the movement of large quantities of materials. Several metals are often bound in the same ore and they are therefore, due to economy and technology, by necessity extracted together. Many scarce metals are only produced as by-flows to more common metals (for example, cadmium from zinc ore, tellurium from copper ore, gallium from bauxite).

Flows can also be related to phenomena which do not directly involve any flow. The cultivation and harvest of biological resources in agriculture and forestry may induce leakage flows of nutrients and give rise to erosion and thus to flows of soil.

In society many flows are performed by transportation means facilitating flows of people, materials, energy and information between different places. The transportation of people and goods is often operated by means of vehicles and other equipment. The use of these facilities in itself constitutes a materials flow. For that function an infrastructure was also built requiring flows of materials in its construction and in its subsequent maintenance and repair.

Different materials flows are thus often intricately interwoven and the indirect flows involved in societal processes are often of great importance for the overall picture.

2.

Nature's turnover of materials

Sustainability requires an adaptation to nature of the material flows induced by society in such a way that the long-run prospects for future generations are met. Which are the natural flows and structures which we have to adapt? We shall here discuss the driving forces in nature and the induced natural turnover of materials on Earth; especially the stocks and cycles of important chemical elements.

2.1 The driving forces in nature

The amount of materials on Earth is nearly constant: the exchange of matter with space is indeed very small compared to the flows on Earth. The energy coming in from the Sun is balanced by a an outflow of energy in the form of heat radiation into space. So which are the forces driving all the processes on Earth; which are the exergy sources? Since the birth of the solar system and the Earth, materials flows on Earth have had three different exergy sources:

(i) the energy flow from the Sun on its way into space

(ii) the energy flow from various processes within the Earth, the lithosphere, which today are dominated by radioactive decays

(iii) the energy from gravity and rotation within the solar system (causing tidal phenomena).

The exergy flow from the Sun/space system is much larger than the other two types of exergy flow and is about 10,000 times larger than the societal use of exergy or energy.

2.2 Ecosphere and lithosphere and geological materials flows

When discussing the long-term interaction between society and nature, it is convenient to distinguish that part of the Earth which directly or indirectly maintains its structures and flows by using exergy from the Sun/space system (and to a small extent tidal exergy). We will here call this part of the Earth the ecosphere. (Others have named this whole the biosphere.) With this definition, the ecosphere contains all living organisms (the biota), the atmosphere, the hydrosphere and the free layer of soils above the bedrock (the pedo-sphere).

We shall use the word lithosphere for the rest of the Earth, the non-ecosphere, that is, the core, the mantle and the crust.

Our definitions of the 'spheres' deviate from current usage, mainly by excluding the pedosphere from the lithosphere. But, as we shall see, when analyzing the flows of materials in a sustainability perspective, our definition has many advantages, because of the tight connection between the pedosphere and the rest of the ecosphere. The important exchange of matter between the ecosphere and the solid litho-sphere takes place largely through the more mobile pedo-sphere. Sustainability implies restrictions on the anthropogenic flows of matter from the litho-sphere to the ecosphere.

The exergy-driven flows in the ecosphere and the lithosphere are maintaining various structures away from chemical equilibrium. These structures are seldom static but have changed along with evolution on Earth. On this geological time-scale, these structural changes represent unfathomable flows of matter where the entire surface of the earth has been exchanged.

In the lithosphere, established heat gradients drive slow but continuous transformations and flows of materials in various geological processes such as plate tectonics. Through these processes the primitive crust has evolved into the present division between the lighter continental crust and the heavier oceanic crust. A large-scale differentiation of the composition of the mantle and the upper and lower parts of the continental crust has also evolved.

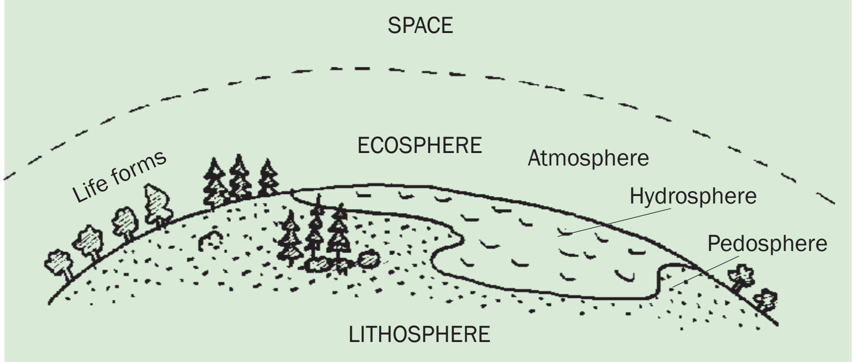


Figure 2.1 The ecosphere contains all living organisms (the biota), the atmosphere, the hydrosphere and the free layer of soils above the bedrock, the pedosphere. The bedrock itself is part of the lithosphere which denotes the rest of the Earth, the non-ecosphere. The lithosphere consists of an inner core, a fluid mantle and an outer solid crust.

The oceanic crust is the product of the internal processes that produce magma in the mantle, driven by the Earth's internal heat generation. The continental crust, unlike the oceanic crust, is long-lived and very little of it is ever recycled back into the mantle. Instead it is subjected to lateral and vertical forces from internal processes that move it around, change its elevation, produce deformations and expose its contents to external processes of weathering, erosion and sedimentation, each of which is to a large extent driven by the exergy of the Sun/space system.

In the ecosphere, the atmosphere and the ocean have evolved into their current composition through the balances of inputs and outputs of materials. The atmosphere has developed into essentially a mixture of nitrogen and oxygen, both derived through the input from biotic processes. Sea water contains per each kilogram 34 to 35 grams of various dissolved elements continuously brought from the crust.

The biota have since their birth early in the history of Earth expanded dramatically and biological life has developed a huge diversity and complexity. The total turnover of mass in life since the beginning has been estimated to be of the same order as the mass of Earth itself. The processes of life are now large and integrated parts of the cycles of the elements in the ecosphere.

2.3 Geophysical flows

Most of the captured solar energy is eventually converted into heat and is balanced through the heat radiation leaving the Earth. These energy flows induce and maintain temperature imbalances and phase changes (for example, evaporation, condensation, smelting) in the cycle of water. The imbalances give rise (through variations in density) to imbalances in the gravitational field leading to various geophysical flows of materials: mass movements in the atmosphere and the oceans in the form of winds, streams, waves and convective flows. See Table 2.1. The movements are, however, taking place on a rotating planet which significantly complicates the patterns of motion.

Table 2.1. Energy and exergy in some geophysical and societal flows

Sphere	*Flow*	*Energy*		*Exergy*	
		[TW]	*[W/m²] d)*	*[%]*	*[W/m²]*
Ecosphere					
Abiotic					
Radiation	Solar radiation (outside the atmosphere)	170 000	340	100	≈320
	* reflected	50 000	100	30	
	* transformed	120 000	240	70	
	– at the Earth's surface	85 000	170	50	≈130 c)
	– in the atmosphere	34 000	68	20	1 a)
Atmosphere	Heat radiation, net to the atmosphere	–86 000	–171		–5.6 a)
	Sensible heat, net to the atmosphere	13 000	25	7	3.5 a)
	Water cycle	42 000 g)	85	25	9 a)
	Wind generation	1500	3	0.1	3 b)
	Internal irreversible processes	0	0	0	– 6 b)
Land/sea	Salt gradient	0	0	0	0.006
Sea	Streams, waves	3	0.006		0.006
	Tidal energy	3	0.006		0.006
Biotic					
Biota	Photosynthesis	100	0.2	< 0.1	0.2
Lithosphere	Heat to the ecosphere	30	0.06	0.02	≈0 f)
	* of which volcanoes + geoth. sources	0.3			≈0.1
Technosphere	Energy in society	13	0.03	0.01	≈energy e)
	* food	0.7			
	* materials	1			
	* energy h)	11.7			

a) exergy flow to the atmosphere, $T_{o,atm} \approx 255$ K, [Karlsson 1990];
b) exergy flow in the atmosphere, [Karlsson 1990];
c) assumed 50% direct, $\eta_B \approx 0.92$; 50% diffuse, $\eta_B \approx 0.73$;
d) mean over Earth's surface: $\approx 5 \cdot 10^{14}$ m²;
e) the energy sources used in society is of high quality=> exergy ≈ energy;
f) at the Earth's surface is the exergy zero, but heat can be extracted from greater depth where the temperature and thus the exergy is higher;
g) liquid water is assumed to be the reference energy level for water;
h) 1990 according to World Energy Council;

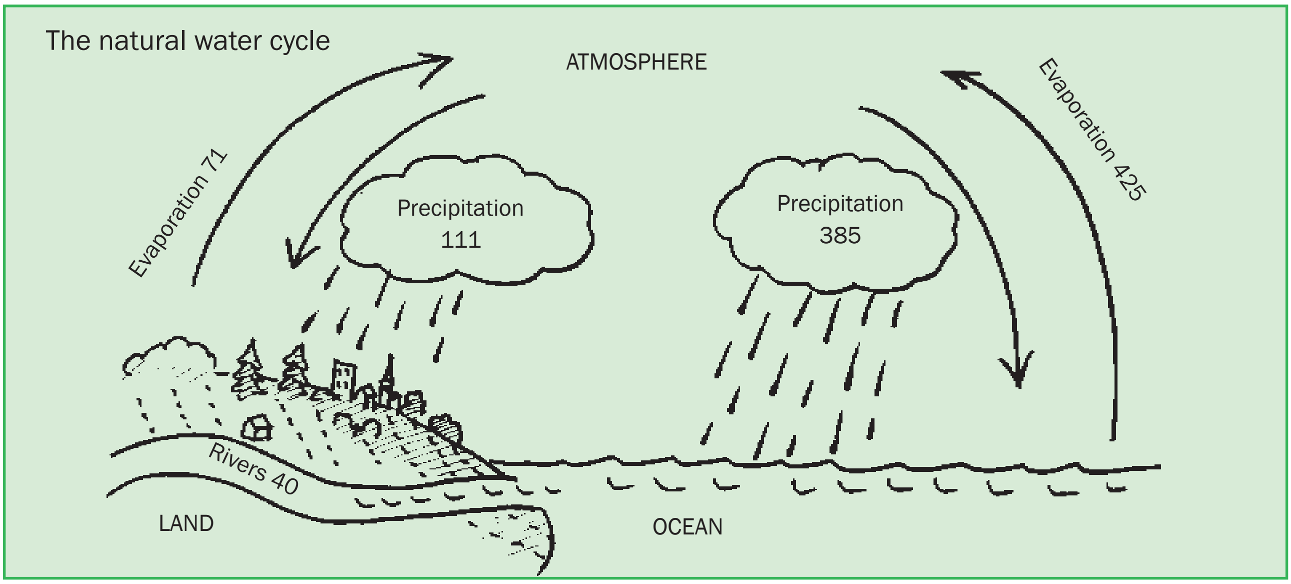


Figure 2.2. The most important geophysical flow is the turnover of water. In a large-scale cycle, water is forced between oceans, the atmosphere and the continents. Evaporation from the sea, ice, and the continents to a gaseous state in the atmosphere involves about one-quarter of the solar energy falling onto the Earth and amounts to about 500,000,000 Mtonnes of water each year or one tonne per m^2. (The numbers denote millions Mtonnes.)

2.4 Geological processes and lithosphere-ecosphere exchanges

We are interested mainly in those lithospheric processes and flows which are of most importance to society or to the ecosphere. The ecosphere is placed on the surface of the crust and is dominated by the geophysics and biogeochemistry of the most abundant elements.

All major rocks in the Earth's crust are dominated by silicate minerals containing the most common elements: silicon, oxygen, aluminium, iron, calcium, sodium, magnesium, and potassium. Oxides of aluminium and iron are also abundant. These common elements make up 99.5 per cent of the crust. The silicates are polymerized in various minerals as in quartz, SiO_2. Aluminium may replace some silicon atoms within the silicate lattice. The negatively charged silicates contain positive ions of metals such as calcium, sodium, magnesium, potassium, aluminium and iron.

The most important minor mineral families are based on negatively charged ions of carbon and sulphur; carbonates, sulphides and sulphates. These mostly form minerals with the six most common cations mentioned above. The general chemistry of the crust is therefore largely that of silicate minerals, with a blending of a few oxide minerals plus carbonates of calcium, magnesium and iron, the sulphides of iron and the sulphates of calcium.

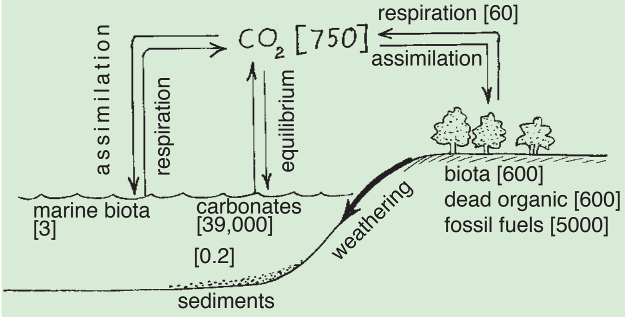
Other elements, for example most metals, are therefore scarce. However, processes within the lithosphere as well as processes at the surface of the Earth have locally led to high concentrations of specific minerals that are useful to society. But these geological processes are, from a societal point of view, very slow and the created concentrated resources can be considered as given finite and exhaustible stocks. Any smaller region, like the Baltic region, will continue to be dependent on the import of many important raw materials, like metals, mined at specific places around the world.

Natural materials flows from the lithosphere to the ecosphere are produced by continental and submarine volcanic activity and through weathering processes. At the Earth's surface there is thus a net flow of materials from the continental crust to the sea and the continental surfaces are continuously broken down. Weathering of the primary silicate minerals from the crust produces the important clay minerals which, together with organic materials, have large capacities for the exchangeable storage of cations and for holding water thus contributing strongly to the natural fertility of soils. Elements dissolved during weathering may either be kept in the soil profile developed from weathering-products and residues or be leached and transported to the sea as particles or dissolved in water. Rivers dominate the transportation of weathering-products and the materials flow to the ocean is estimated to be around 20,000 Mtonnes per year.

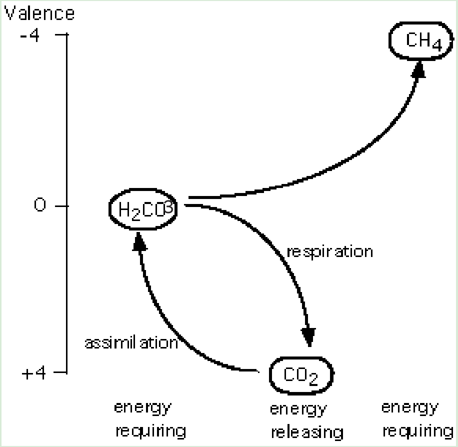
In the sea, the elements are, to various extents, accumulated but ultimately go into the sediments. The sedimented material may, on a geological time-scale, be fed back to the continental crust through uplifts or upward movements of melted material. Although the crust contains only 5 per cent sedimentary rocks, at the Earth's surface, three-quarters of the crust is sedimentary rocks.

Generally, however, these flows between the lithosphere and the ecosphere are much smaller than the flows within the ecosphere. Thus the ecosphere can be characterised as a nearly closed system.

THE NATURAL CARBON CYCLE

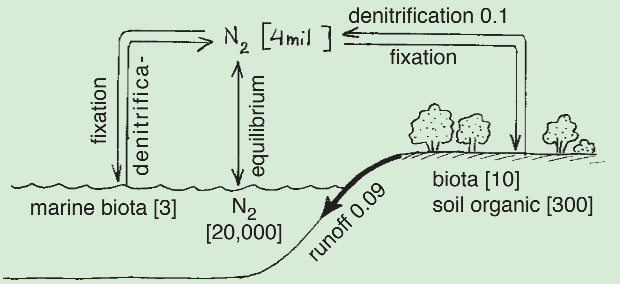


Carbon is available in the ecosphere as inorganic oxidized carbon in the form of carbon dioxide in the atmosphere or dissolved in sea water to form carbonates. A large amount is also in reduced organic form in living organisms or in dead organic matter in the soil and the sea. A rapid turnover between these two pools occurs through photosynthesis. The inorganic and organic pools correspond to around 400 and 20 years of photosynthesis, respectively. The reduced carbon stowed away in the lithosphere in the form of available fossil fuels is, if it is used up, large enough to change significantly the carbon concentrations in the ecosphere. It then ends up in the inorganic pool residing in the atmosphere and the sea. A lot of carbonates have gone into sediments in the sea and are balanced by uplift of sediments and volcanic degassing of carbon dioxide. (Numbers in thousands Mtonnes.)

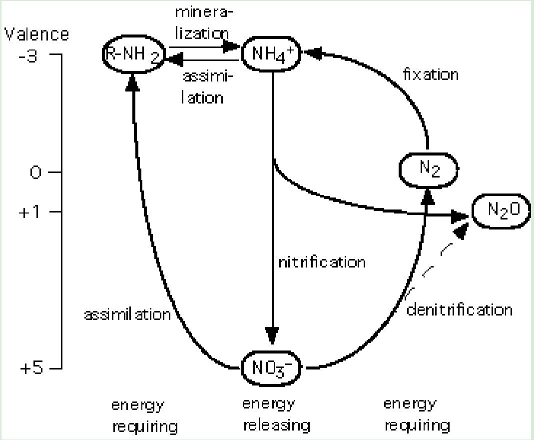


The biogenic parts of the carbon cycle. Plants extract carbon dioxide from the atmosphere and incorporate it in various organic molecules such as carbohydrates, fats and proteins. Subsequent use of the organic material in respiration by the plant or heterotrophic organisms, such as animals, results ultimately in an oxidization back to carbon dioxide. In anaerobic environments, some micro-organisms can use organic materials, instead of oxygen, as electron acceptors. The carbon can then be reduced to methane, which is oxidized back to CO_2 in the atmosphere.

THE NATURAL NITROGEN CYCLE

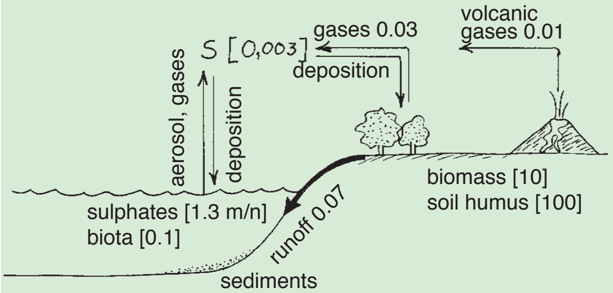


The Earth's crust contains relatively small amounts of nitrogen, and most of the nitrogen in the ecosphere exists as a biochemically and biophysically inert gas (N_2) residing in the atmosphere. Approximately one per cent is dissolved in the oceans. However, from an environmental point of view, the interesting part of nitrogen is not this inert pool, but the chemically and biologically active part, the so called 'fixed nitrogen' in the ecosphere. Nitrogen is fixed in the ecosphere and brought into biogeochemical cycles mainly by certain specific nitrogen-fixing micro-organisms. To some extent it also occurs geophysically in lightning. A certain inflow of fixed nitrogen, as well as of sulphur, from the lithosphere also takes place through volcanoes. (Numbers in Mtonnes).



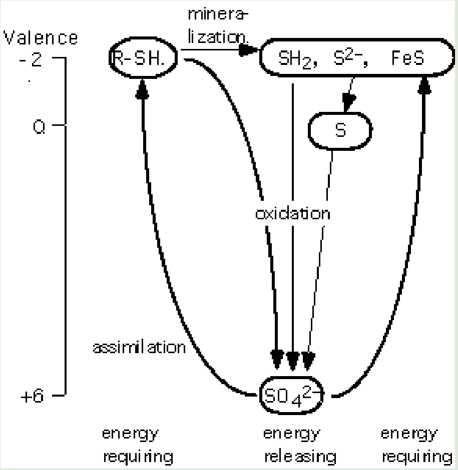
The biogenic part of the nitrogen cycle. Plants may extract nitrogen from water in the soil either as ammonium or nitrate. The nitrogen is incorporated mainly in protein. Subsequent mineralization of the organic material results in ammonia (NH_3) which, in aerobic conditions, is used by micro-organisms as an energy supply and oxidized back to nitrate. In anaerobic environments, some bacteria can use nitrate ions, instead of oxygen, as electron acceptors. The nitrogen is then normally reduced to the inert nitrogen gas (N_2), or to some extent to dinitrogen oxide (N_2O).

THE NATURAL SULPHUR CYCLE



In the Earth's crust, sulphur is mainly found in minerals as sulphides (–S^{2-}). In the soil at the Earth's surface, it is oxidised and sulphate ions (SO_4^{2-}) available to plants are produced by weathering processes and micro-organisms. Sulphate is easily leached. The sea has a large pool of sulphate ions deposited from the air and leached from continents. Ultimately it goes into the sediments; for example as gypsum. Though sulphate is easily leached from the soil, it is normally available in sufficient quantities not to limit plant growth.

To the atmosphere volcanic activity emits sulphur mainly in the form of sulphur dioxide, while biota release mainly reduced gases, such as dimethylsulphide (DMS) and hydrogen sulphide. Sulphuric compounds are withdrawn from the atmosphere by dry and wet deposition. Sulphate is transferred from the ocean to the atmosphere in water droplets which quickly evaporate. (Numbers in Mtonnes).



The biogenic part of the sulphur cycle. Plants extract sulphate from water in the soil. The sulphate ions are reduced and incorporated mainly in amino acids. Subsequent mineralization of the organic material results in hydrogen sulphide (H_2S) which, in aerobic conditions, is quickly oxidized back to sulphate or in some cases to pure sulphur. In anaerobic environments, some bacteria can use sulphate ions, instead of oxygen, as electron acceptors. The sulphur is then reduced to, for example, hydrogen sulphide.

2.5 The living processes and the bio-geo-chemical cycles

Embedded in the surface processes are the living processes. Some of the solar exergy flow through the ecosphere is captured in photochemical reactions taking place mainly in the atmosphere and in the biochemical photosynthesis in the biota.

Photosynthesis

Photosynthesis modifies the flows of many elements and maintains new chemical disequilibria. In this way it contributes to the maintenance of the large so-called biogeochemical cycles of various elements; especially the elements carbon (C), hydrogen (H), sulphur (S), nitrogen (N) and oxygen (O). Photosynthesis reduces carbon, sulphur and nitrogen and incorporates them, together with hydrogen, in organic materials of growing plants. Oxygen is oxidized from water into oxygen gas, O_2, going into the atmosphere. Also, a large part of the continental evaporation of water is accomplished through trans-piration by the biota.

The incorporation in plants of C and H, as well as N and S, is strongly endothermic, that is, requires energy and exergy. Captured solar exergy is transformed into chemical exergy of the chemical bonds in carbohydrates and other organic materials. The overall chemical balance of photosynthesis can be written as:

carbon dioxide + water + light –> carbohydrate + oxygen

Respiration

The exergy-rich organic material is used by plants in their own respiration or by heterotrophic organisms (animals, micro-organisms and other decomposers) eating plants and is eventually oxidised back into inorganic forms.

Parts of the reduced elements have escaped oxidation and gone into the sediments and now exist mainly as dispersed solid material in sedimentary rocks; mainly in shales. A small fraction of this reduced carbon is present as recoverable resources of coal, oil and natural gas. However, the major part of the carbon in the crust is present as carbonates.

The corresponding free oxygen created by photosynthesis has slowly accumulated in the atmosphere which has made large parts of the ecosphere strongly oxidative. At the Earth's surface the equilibrium states of carbon, nitrogen and sulphur are therefore in their oxidized states. The composition of the atmosphere is to a large extent determined by these life processes. Besides oxygen, the nitrogen in the atmosphere is also held away from thermodynamic equilibrium, which is as nitrate.

Turnover of carbon, nitrogen and sulphur

The biotic turnover of carbon, nitrogen and sulphur consists to a large extent of similar or corresponding oxidation-reduction reactions. To incorporate and reduce these elements, much energy is required and, in the subsequent oxidation, energy is released. Certain micro-organisms can use the oxidation of reduced nitrogen and sulphur for their energy supply.

Reduction and oxidation requires an electron donor and acceptor, respectively. In the ecosphere, oxygen normally is the oxidizer or electron acceptor.

Various gaseous compounds are emitted to the atmosphere. They or their reaction products (the atmosphere oxidizes chemical compounds with varying efficiency, leave the atmosphere by absorption or dry deposition. If easily dissolved in water, they can quickly be washed out from the atmosphere with the rain: wet deposition.

Turnover of phosphorus

Phosphorus is a vital element in all living systems. It is a component in, for example, nucleic acids, membranes and energy transfer in cells. Calcium phosphate is the basic component in bones and teeth of animals. The turnover does not involve any oxidation-reduction reactions.

Phosphorus is absorbed by plants from the soil solution in the form of phosphate ions and is essentially in this form during the whole cycle. Contrary to C, N, and S, there is no natural common gaseous form of phosphorus, which can contribute to an efficient redistribution of phosphorus between different ecosystems. Once lost through any leakage, it cannot be easily compensated for.

In the crust, phosphorus is found bound to oxygen in various phosphate minerals; to the extent of about 95 per cent in apatites. In soil, however, most of it exists in the form of insoluble, organic or inorganic, compounds and is not directly accessible for plants. Its availability to plants is dependent on pH; the highest availability is at pH between six and seven.

Turnover of nutrient cations

The base cations (calcium, magnesium, sodium and potassium) are important nutrients and are absorbed by plants from the soil solution as positive ions. They are available in large quantities in the crust in common silicate minerals or sediments and are released in weathering. In soil, they also occur in exchange positions in clays and humus (dead organic matter). They are easily leached and, together with the carbonate and sulphate ions, form the most common minerals in fresh water.

2.6 How society interacts with natural flows

The societal physical influence on nature is characterized by two different types of interaction: *exchange* of energy and materials and by *manipulation* of nature, (see Fig. 2.3). Exchange of energy has two sides: exchange takes place in the form of

- *extraction* of resources, energy and matter from nature and
- *emissions* (*return flows*) of energy and matter into nature.

Human society uses exergy and matter from the ecosphere and lithosphere to compensate for losses, to maintain processes and to build up new structures within the material side of society, which we shall here call the *technosphere*. Manipulation comprises various material rearrangements within nature, that is, influences which do not imply an exchange of materials with the technosphere.

The resources extracted, that is, specific materials or flows in nature in a concentrated form, can be characterised according to their sources and renewability: resources are extracted from natural flows, funds and deposits for use in the society.

- *Natural flows* are continuously flowing materials and energy fluxes ultimately driven by the exergy flows (for example, sunlight and winds) coming into the ecosphere. If not used, they are eventually dissipated naturally.
- The *funds* are pools of materials accumulated and regenerated with the help of natural flows (for example, forests, fish populations, clean air and water). Their capacity for regeneration gives an absolute potential for the long-run rate of extraction.
- The *deposits* are pools of materials (for example, minerals and ores)with such long regeneration rates, if any, that they are gradually depleted as extracted.

This applies to the lithospheric deposits accumulated on geological time-scales. However, some ecospheric pools also have long turnover times compared to society. For example, peat accumulated since the latest ice age ten thousand years ago may in this perspective be considered as a non-renewable stock.

The extraction of renewable resources involves impacts on resources which may severely limit possible sustainable extraction rates far below the limit set solely by regeneration capacity. Hydropower schemes can change water flows and influence ecosystems along a whole river and harvesting in forests may shift the composition and the frequency of old, but ecologically important, trees.

Extracted materials that are not stored or accumulated in the technosphere are returned to nature, in accordance with the law of conservation of matter. The capacity of the ecosphere to degrade, remove or assimilate these flows in the cycles of nature depends on the type of flow. There are, as with resources, flow capacities which can manage a certain rate. For example, there is the capacity of a water body to decompose organic materials or to transfer materials to sediments out of reach for important life processes or stock capacities which are more characterized by limits on accumulated amounts that can be coped with without disturbing functioning: there is, for example, a limited capacity of soil to accumulate heavy metals

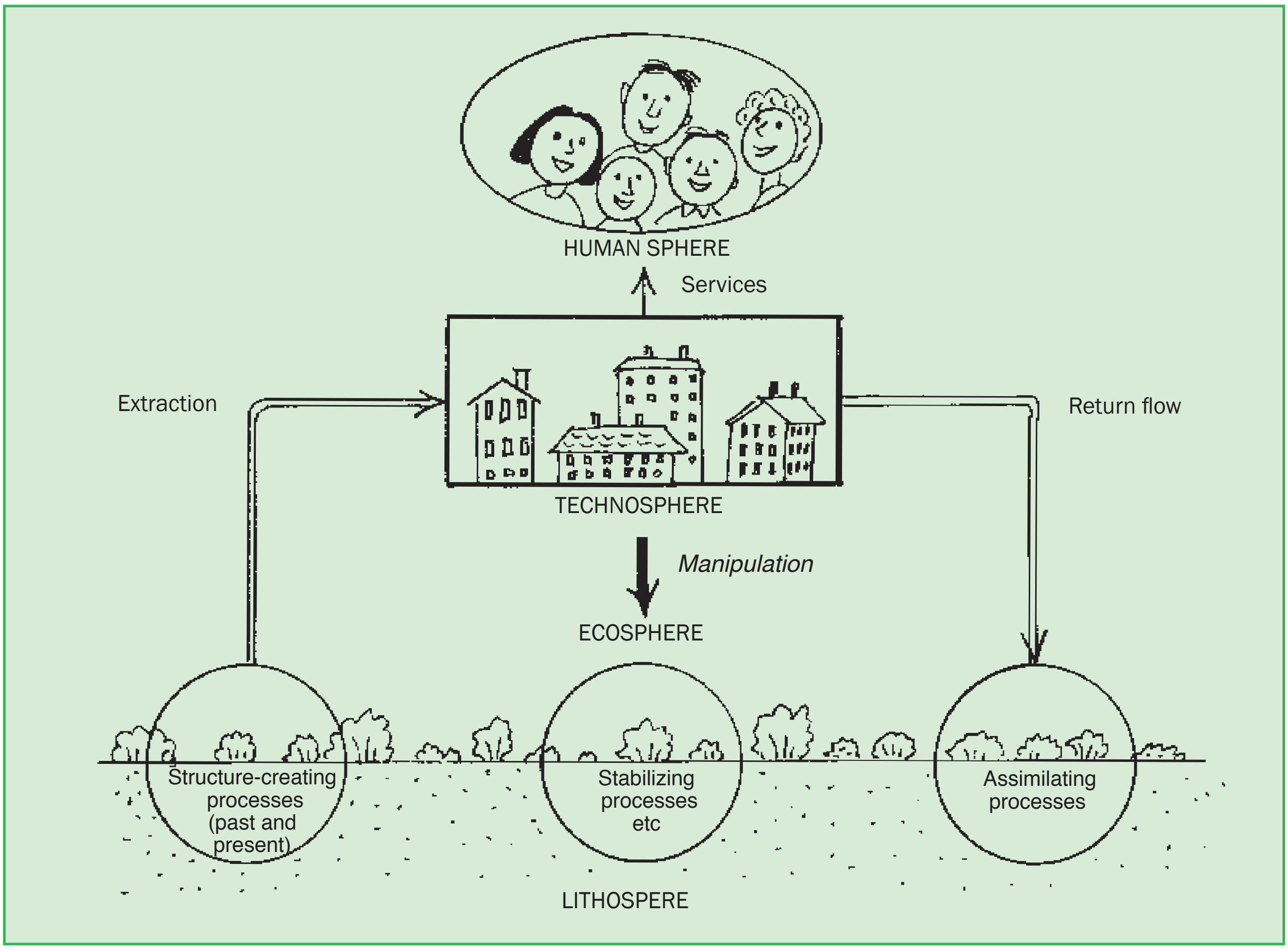


Figure 2.3. A general picture of mechanisms for the physical influence of society on nature. The various parts, the lithosphere, ecosphere, technosphere and human sphere and their borders, are here illustrated by geometric shapes, but in reality their interactions are complex and they have very complex interfaces. (Based on Holmberg & Karlsson [1992]).

and a limited capacity of the ecosphere to accumulate carbon.

The societal manipulation of nature includes:

(i) *displacement* of nature (societal activities force away or disturb ecological systems or geophysical functions by, for example, the construction of highways, etc.),

(ii) *reshaping* the structures of nature (for example, the damming of rivers, ditching and ploughing) and

(iii) *guiding* processes and flows (for example, in agricultural practices and the manipulation of genes).

Nature has a limited resource-creating capacity for the substances that society extracts as well as a limited assimilation capacity for the substances that society returns to nature. Furthermore, the stabilization capacity of nature is often reduced when it is manipulated, for example, through the loss of biodiversity.

Society also has an immaterial part, the *human sphere*. The technosphere with its structure and flows of materials and energy delivers certain *services* to the human sphere. These services are the immaterial part of resource use and, therefore, a service does not contain any material or energy. For example, an electric heater in an apartment gives an energy flow which is then leaked to the surroundings. The service provided in this process is a certain indoor climate. It is possible to increase the service flow without increasing the exchange of matter and energy with nature, by increasing the efficiency of the internal physical flows within the technosphere, that is, more service can be delivered per unit of exchange with nature.

We should also not forget that nature itself is delivering services more or less directly to the human sphere with negligible physical interaction involved when, for example, we enjoy beautiful scenery, feel pleasure from the sole existence of various species, and learn from nature.

MIPS = Material Intensity

How are large flows of materials in one form or another and with potential ecological significance needed (or induced) to provide a certain service in society? The Wuppertal Institute has developed the MIPS concept (Materials Input Per Service unit) in order to answer this question. MIPS works with the following five main input categories of material flows:

I. ABIOTIC RAW MATERIALS

This category contains:

- all fossil fuels, including peat;
- mineral raw materials, for example, sand and gravel, crushed rock and stone, clays, metal ores, and industrial minerals;
- overburden and other materials translocated to reach valuable materials, that is, the materials excavated together with valuable materials for later separation and the materials that must be moved in order to make excavation possible;
- excavated and dredged materials, that is, translocated materials like rock, soil and spoil used for levelling and putting in order the infrastructure.

II. BIOTIC RAW MATERIAL

These include:

- biomass both from human-maintained and natural ecosystems. (Animal products from agriculture are not included, but the fodder needed to feed the animals is included).

III. SOIL MOVEMENTS (in agriculture and forestry).

These include:

- the working of soils in agriculture, for example, ploughing;
- the erosion of soils due to human activity.

IV. WATER

This includes:

- water used in chemical processes;
- water in hydro-power stations (Water in run-of-river hydro-power stations, where there are no changes in the through-flow, is excluded.);
- water used for cooling;
- water used in actively arranged irrigation;
- water drained or drawn off, including rainwater from hard made surfaces such as roads and roofs, water from drained wetlands and mines;
- water in canals that is drawn from natural water courses.

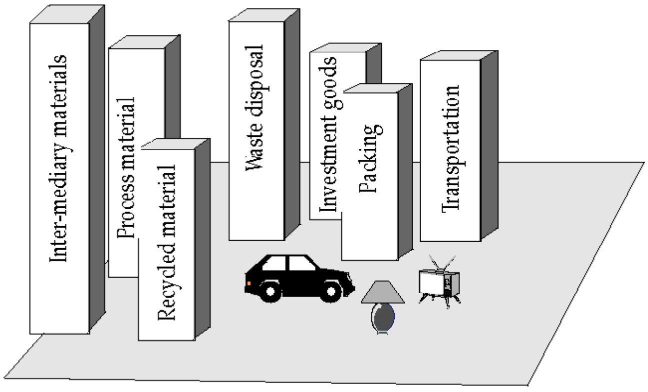
V. AIR

This includes:

- air used in combustion;
- air used as a raw material in chemical or physical processes.

  (However, air used in ventilation and cooling, compressed air and the through-flow in wind-power generation is excluded.)

The ecological rucksack



The MIPS measure gives the weight of material extracted from nature to obtain a certain service. Of the extracted material there is a useful part, which provides the service, and a non-useful part, called the rucksack. The return flow to nature, and its environmental impact, is not included in MIPS.

As an example, the MIPS measure of transporting oneself a distance with a car etc. is shown to the left. The rucksack, due to the extraction of various metals, etc. from nature, is normally much larger, sometimes several hundred-fold larger, than the material in the consumer goods itself.

3.

HUMAN-CAUSED MATERIAL FLOWS

Industrialized society is an enormous mobilizer of materials. We shall here discuss the size and the overall characteristics of these anthropogenic flows. We shall introduce the MIPS concept which has been developed to catch and describe the overall mobilization. Overall material flows will be described both for global human society and for some countries where specific studies have been done: Germany, the United States and Sweden.

3.1 MIPS: a materials intensity concept

Materials intensity is a measure of the amount of materials used to provide a certain amount of service. How are large flows of materials in one form or another either extracted from nature and fed into society to provide a certain service or, in an environmentally potentially significant way, mobilized in any way in nature to provide this service? The Wuppertal Institute for Climate, Environment and Energy in Germany has developed the MIPS concept (Materials Intensity Per Service unit) in order to answer this question.

MIPS works with the following five main input categories of materials flows: water, air, abiotic raw materials, biotic raw materials and soil movements (in agriculture and forestry). All the materials flows are measured by their weight. Different qualities like emissions, exhaustion of resources and the extent of the manipulation of nature are connected to these materials flows leading to, for example, various environmental damage and effects on health.

There are of course tremendous differences in the specific effects, effects per kilogram of material, caused by different materials flows or emissions, even if various sectors in society always use different combinations of materials, and therefore the effects might vary considerably. Thus, it is still of interest to show all the flows in terms of a common unit of measurement and weight is probably the most convenient one. What do the overall materials flows in industrialized society look like? Which flows dominate and what are the characteristic features of societal metabolism?

Fig 3.1 The human-caused solid material flow is dominated by sand and gravel used for construction of infrastructure, and mining wastes.

Table 3.1 Domestic overall account of the materials mobilization of Germany 1991 [Bringezu et al., 1995].

INPUT			OUTPUT		
	Total Mtonnes	*kg per capita & day*		*Total Mtonnes*	*kg per capita & day*
Water	**69 290**	**2 373**	**Water**	**69 290**	**2 373**
– Used	46 874	1 605	– Treated	13 857	475
– Unused	22 416	768	– Untreated	32 573	1 116
– Imports	0.2	0.00005	– Water losses and evaporation	5 395	185
			– Water diversion	17 459	598
			– Water exports	8	0.3
			Emissions to water	**34**	**1.2**
			– Dredging excavations	34	1.2
			– N and P from sewage	0.4	0.0001
Air	**781**	**27**	**Emissions to air**	**2 919**	**100**
– O_2 for combustion	725	25	– Water	1 850	63
– Production of O_2 and N_2	38	1.3	– CO_2	1032	35
– O_2 for steel production	18	0.6	– NO_x, SO_2, CO	20	0.7
			– Others	17	0.6
Abiotic raw materials	**3993**	**137**	**Waste disposal**		
– Used • minerals	829	28	**(excluding incineration)**	**2 891**	**99**
• ores	0.4	0.0001	– Controlled waste deposition	222	8
• energy carriers	366	13	– Landfill and mine dumping	2 669	91
– Unused • non-saleable prod.	2532	87			
• excavation	266	9			
Biotic raw materials	**82**	**2.8**			
– Plant biomass from cultivation	82	2.8			
– Fishing/hunting	0.4	0.0001			
Soil			**Soil**	**166**	**5.7**
– Erosion	**129**	**4.4**	– Erosion	129	4.4
			– Dissipative use of products		
			• fertilizers	35	1.2
			• sewage sludge	0.8	0.0002
			• compost	0.8	0.0002
			• pesticides	0.03	0.0001
Import	**433**	**15**	**Exports**	**211**	**7.2**
			Waste for utilization (stored)	64	2.2
			Accumulation (balance)	1 047	36
TOTAL			**TOTAL**		
– With water	**74 708**	**2558**	– With water	**74 350**	**2546**
– Without water	**5 418**	**186**	– Without water	**5 060**	**173**

3.2 Mobilization of materials: the German example

A materials flow account of the German economy showing the input and output of materials is presented in Table 3.1. The input is estimated according to the MIPS concept. Extracted useful materials are, after various degrees of transformations in the production system, used to serve different parts of the economy. Materials will end up in various output streams, possibly after a limited time of accumulation and recycling in the technosphere, in handled waste or in various emissions or losses to parts of the ecosphere. They may also be left behind when no longer in use as, for example, cables left in ground when obsolete. We shall start with the five MIPS categories when describing the total input and overall mobilization of materials.

Water is the totally dominating mobilized material in the German economy (Table 3.1): 69 billion tonnes per year corresponding to a daily water flow per person of 2.4 tonnes or cubic meters. The water flows accounted for here are generally the flows which are deviations from the natural flows or withdrawals from natural storage. The flow figure still does not include water corresponding to the natural evapotranspiration from growing plants cultivated and harvested in agriculture and forestry. These flows are even larger than those accounted for. It is estimated that each kilogram of dry biomass grown requires 150 to 800 kilograms of water in evapotran-spiration.

The minor amount of the mobilized water is consumption or losses of fresh water, defined as fresh water that has been evaporated, transpired or incorporated into products, plant or animal tissue and is therefore unavailable for immediate reuse. The major amount is water flows that to various extents are deflections in space and time of natural flows or storage. However, the environmental importance may still be large because of the ecological significance of water availability and humidity levels. About one-third is unused water that is withdrawn for drainage only, for example, in mining and in rainwater drainage.

Air flows included in the MIPS are the flows in which air is used as a raw material. Air is mainly consumed in the combustion of fuels and is thus very strongly connected to the flow of fuels. The minor amount is used in industrial processes such as iron production. Each kilogram of unoxidized carbon in a fuel needs 2.7 kilograms of oxygen when burnt and producing carbon dioxide. The corresponding figure for the fuel hydrogen is 8 kilograms of oxygen when it is burnt to water. This means that 1 kg of oil or gasoline uses 3.4 kg of oxygen or 11 m^3 of air for combustion.

However, the amount of air used is negligible compared to the total amounts available. Approximately one per cent of the oxygen in air corresponds to the estimated available total resources of fossil fuels and the living and dead organic materials in the ecosphere. Thus, air is inexhaustible and not a resources problem, but possible problems are related to air pollution. The pumping of air in industrial processes such as combustion and filtering, and in heating, cooling and ventilating buildings also requires resources (for example, electricity).

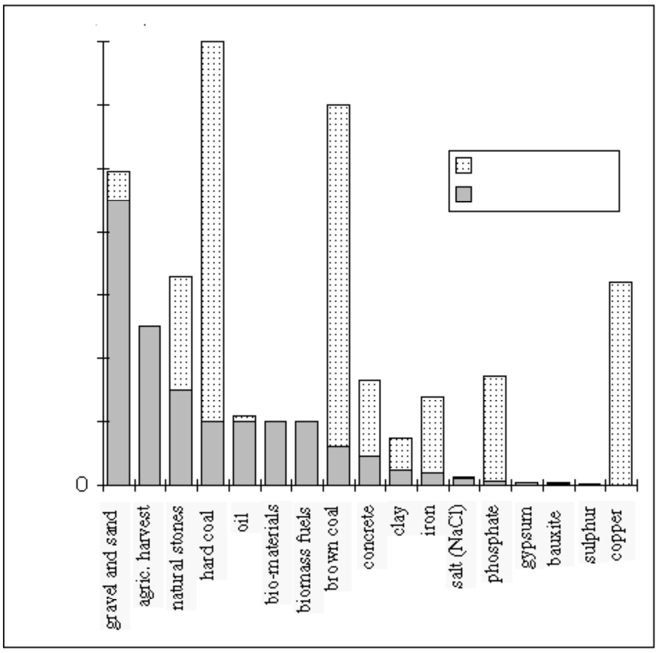


Figure 3.2. Global anthropogenic extraction of lithospheric materials (estimated from Schmidt-Bleek & Tischner [1995]), and global harvest of ecospheric materials in the form of biomass (Mtonnes/year) [Karlsson et al. 1996].

3.3 The ecological rucksack

The abiotic raw materials are extracted both from the litho-sphere and from the soil in the ecosphere. Connected to the extraction of useful materials is an ecological 'rucksack' [Schmidt-Bleek 1994], namely, the flows of materials that are not included at all in products but are a necessary part of extraction or are more or less unavoidable by-flows. Overburden has to be moved to obtain the useful materials and ores exposed to the applied extraction methods. Furthermore, high-value metals like copper are extracted from metal ores which hold only small amounts of metals. (The grade of copper ore can be as low as about 0.3 per cent.) The non-metal remainder is discarded in the refining process and is part of the rucksack.

The German annual domestic extraction of abiotic materials is about 4,000 Mtonnes or 50 tonnes per capita. Of this, about one-third is non-saleable materials like overburden. The market for metals and fossil fuels is to a large extent global. Densely populated industrialized countries are naturally often net importers of abiotic materials. The German rucksack connected to imports is nearly as large as the domestic one.

In industrialized countries the flow of renewable organic materials in the form of harvested biomass is inferior to that of exhaustible fossil organic materials (in the form of fossil fuels). In Germany the domestic energy carriers are more than 4 times larger than the biomass harvest, which amounts to 82 Mtonnes/year, or almost one tonne per capita. Total domestic abiotic materials extractions are about 50 times larger than the biotic ones. Inclusion of the net imports will raise this figure further.

In Germany the estimated amount of erosion associated with the input of biotic raw materials from cultivation exceeds even the dry weight of these raw materials. The erosion to biotic raw materials ratio has also increased during the 1980s.

The working of soils in agriculture (for example by ploughing) is not included in the figure for soil movements in Table 3.1. However, this mobilization is very large. If, say, half of the agricultural land of about 0.3 ha per person in Europe is ploughed every year to a depth of 0.2 metres, this annual movement of soil is about 600 m^3

or 1200 tonnes per capita which is very large compared to other flows except water.

3.4 Global anthropogenic flows

Major world-wide societal extractions from the lithosphere together with their rucksacks are summarized in Figure. 3.2. The extraction of lithospheric materials amounts to around 20,000 and 60,000 Mtonnes/year without and with the rucksack, respectively, corresponding to 4 and 12 tonnes per capita respectively. Mineral raw materials can be divided into four broad categories of use:

- energy minerals which are the fossil fuels, including peat;
- ore minerals used for the extraction of metals;
- minerals used for their chemical properties as raw materials for chemical compounds and fertilizers;
- minerals used for their special or aggregate physical properties. This diverse group ranges from building materials such as sand, gravel and cement to special industrial minerals for abrasives.

Of the world-wide rucksack amounting to around 40,000 Mtonnes/year, about one-half is due to energy conversion; in practice the use of fossil hard and brown coal. These fuels are mostly extracted by open-cast mining, giving rise to large volumes of overburden. Some metals also contribute to the rucksack: for example, iron, because of its high use volume in society and copper, because of its low grade in ores and some high-volume non-metallic minerals such as minerals for phosphorus and concrete production. These rucksacks consist mainly of large dumps and translocated materials at the mine or refinery. Locally these may give rise to serious environmental effects.

World-wide, the extraction of mineral raw materials is dominated by building materials and energy minerals (fossil fuels), which are consumed roughly on the same scale, around 13,000 and 9,000 Mtonnes/year respectively. Building materials consist mainly of trivial materials like sand and gravel used as filling material and in concrete. Fuel minerals (oil, gas and coal) are used mainly as fuels but also to some extent (around 5 per cent) as feedstock for organic chemicals and materials, like plastics and asphalt. It can also be noticed that metals, except for iron (700 Mtonnes/year), are used in relatively small amounts: for example, aluminium 20 Mtonnes/year and copper 10 Mtonnes/year.

Certain specific industrial minerals are also used in large amounts, especially when employed in high-volume building materials or as filling materials. Examples are limestone and various clays for cement production and gypsum. Raw materials for basic inorganic chemicals and fertilizers are used in relatively large amounts; some of them in much larger quantities than the non-iron metals. This applies to rock salt (NaCl), sulphur-containing minerals (S) and phosphate minerals (P), as well as nitrogen (N) from the air.

Globally, the harvested terrestrial biomass, about 9,000 Mtonnes/year is less than the excavated abiotic materials, but of the same order as the fossil fuels. The biomass is used for three main purposes: food/animal feed, materials and energy. Today these uses amount to 5,000, 2,000 and 2,000 Mtonnes/year respectively. The harvest of the sea in the form of fish catches (around 0.1 Mtonnes) is, on a weight basis, very small (around 2 per cent) compared to the terrestrial harvest. But it is still of great nutritional importance; it accounts for about 25 per cent of the human intake of animal protein.

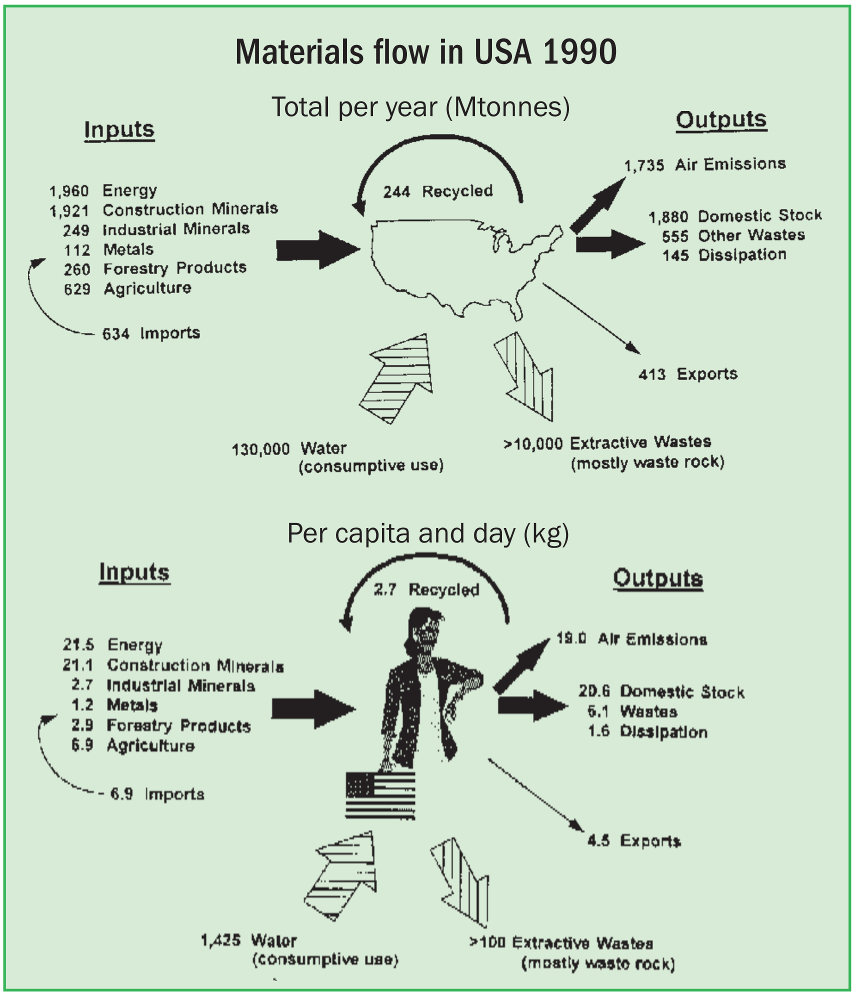


Figure 3.3 Material flows in the United States circa 1990. The materials input is measured as apparent consumption, a) in [Mtonnes/year], b) in [kg/capita and day] [Wernick & Ausubel 1995].

Fig 3.4 The rate of build-up of landfills in industrial societies is now slowly diminishing due to recycling of e.g. scrap metals.

3.5 Intake of materials to the technosphere

As mentioned earlier, of the totally mobilized materials, only a part is brought into society. This intake can be in the form of raw materials for production: either included in goods, infrastructure and other artefacts or consumed in the production of these artefacts or in the production of services. How is this intake of materials into the technosphere made up? The situation in industrialized countries can be illustrated by the account of the American materials balance given in Figure 3.3. The input is here the apparent consumption at the feedstock stage (that is, refined metal, ammonia, crushed stone). Compared to the MIPS material flow inputs, many of the categories are thus missing: air, water, soil erosion and overburden and refining wastes in the extractive industries.

In the United States, energy and construction minerals make up equal shares and together are about three-quarters of the apparent consumption of all materials. The harvest of biological materials corresponds to one-fifth. In industrialized countries, which have a high share of animal products in their diet, the agricultural harvest is dominated by animal fodder. Industrial minerals comprise 5 per cent and metals only 2 per cent, which are, once again, totally dominated by iron. Other metals together make up only 2 promille of the overall intake of materials.

3.6 Accumulation and outflow of materials from the techno-sphere

From materials conservation it follows that the mobilized materials brought into the techno-sphere can either accumulate in the built technosphere or contribute to the outflow of materials from the technosphere. But, of course, the accumulated material will also, sooner or later, give rise to an outflow back to nature. There is a huge difference in these respects between and also within the various groups of materials.

Organic materials are to a large extent oxidised when used. Fuels are burnt giving rise to flue gases of mainly carbon dioxide and water which are immediately emitted to and dissipated in the atmosphere. The agricultural harvest is mainly used to feed animals and humans and is thus to a large extent dissipated in respiration or manure broken down in the soil. However, parts of organic materials are long-lived. There is an accumulation of wooden building materials in the technosphere. Part of organic waste, such as plastics and paper waste, can also stay intact for a long time in landfills.

Fertilizers, which make up a large part of the intake of chemical raw materials and which are used in association with organic materials, are spread dissi-patively into the soil. Also other chemicals, such as road salt, are dissipated in connection with their use.

During industrialization, the input of building materials has to a large extent accumulated in the built environment. Large amounts of sand, gravel, clay and other building materials for houses and roads have not yet been turned into waste. It is also possible that a large part of these

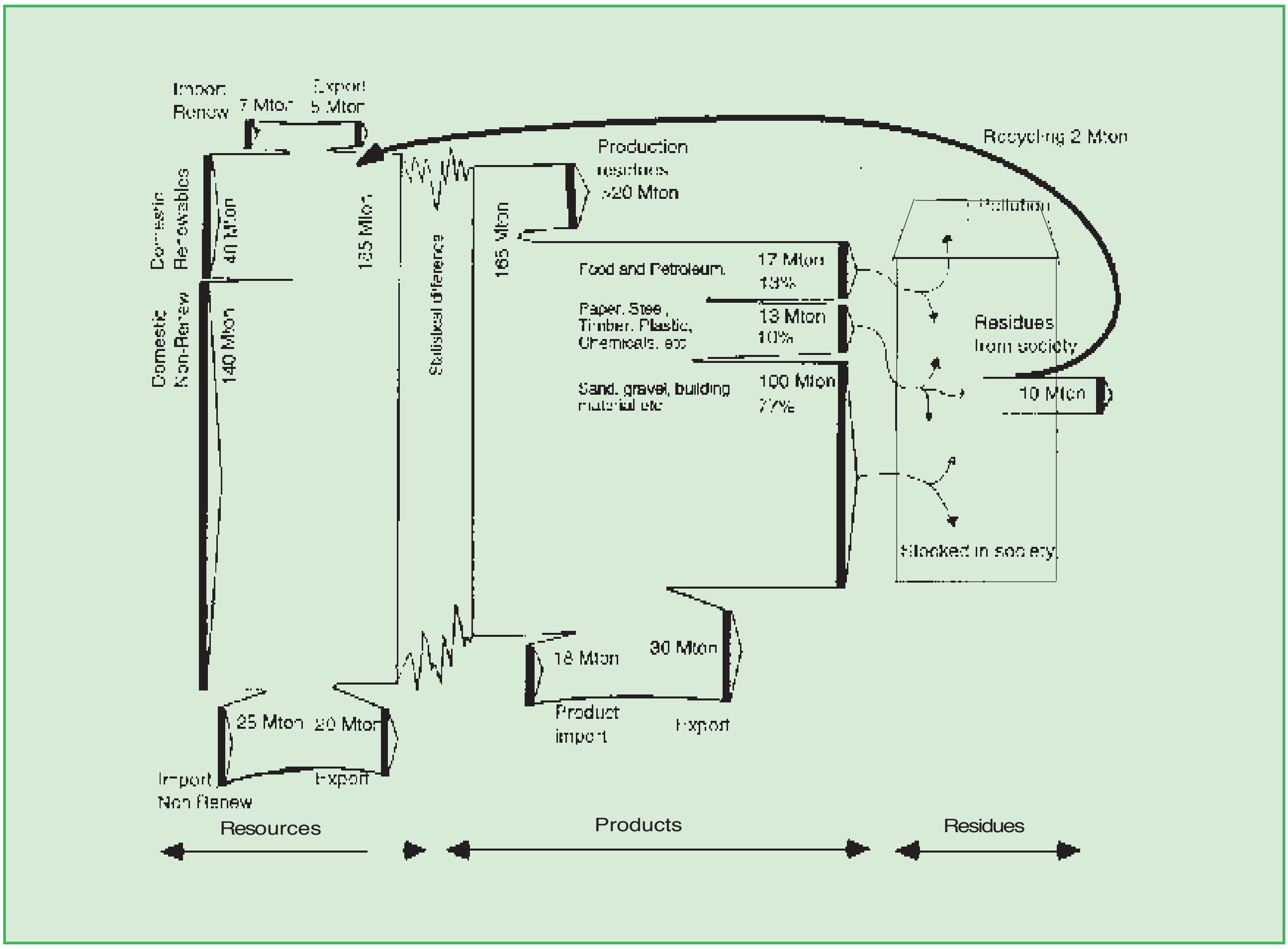


Figure 3.5 Material flows in the Swedish technosphere, 1991. Water use and mining waste are excluded (Mtonnes) [Hunhammar 1994].

materials will never be removed or considered a residue, but will be left when no longer in use as, for instance, the materials in old roads.

For various reasons, there is thus a huge difference in the materials input to society and the amount of solid residues generated and taken care of in one way or another. This can be illustrated with the materials balance for Sweden in 1991; see Figure. 3.5. The net intake to the technosphere was around 150 Mtonnes (165 Mtonnes, minus a net export of 12 Mtonnes), while the generated, mostly solid, residues were around 30 Mtonnes. Of these residues, around 10 Mtonnes were managed by the municipalities, while the rest were various production residues generated in industry.

In Germany, materials accumulation is around 1,000 Mtonnes/year according to Table 3.1. (Another estimate using the production of durable goods has arrived at around 700 Mtonnes/year.) A comparison with the total turnover of 5,400 Mtonnes/year (without water), suggests that the major part, or about three-quarters of the through-flow is dissipated. However, compared to the solid and liquid materials (without water) taken into the techno-sphere (thus excluding air, unused abiotic raw materials, and the erosion of soils), accumulation is a major part.

4.

TOWARDS SUSTAINABLE MATERIALS MANAGEMENT

4.1 Socio-ecological principles for sustainability

In what way do we have to adapt our physical societal metabolism in order to approach sustainability? In the Brundtland report [WCED, 1987], sustainability is described as ”meeting the needs of the present generation without compromising the ability of future generations to meet their own needs.”

As a general rule, we should avoid systematic changes of the ecosphere that threaten the long-term survival of humankind on Earth. This leads to restrictions on our exchange of materials with nature and to our manipulation of nature.

Holmberg et al. [1994] have formulated four general principles for the exchange flows between society and nature and for the manipulation that has to

PRINCIPLE 1

Substances extracted from the lithosphere must not systematically accumulate in the ecosphere.

PRINCIPLE 2

Society-produced substances must not systematically accumulate in the ecosphere.

PRINCIPLE 3

The physical conditions for production and diversity within the eco-sphere must not systematically be deteriorated.

PRINCIPLE 4

The use of resources must be efficient and just with respect to meeting human needs.

Figure 4.1 Based on the characterization of the interaction between society and nature,one can identify general criteria for sustainability. These are formulated into guiding principles for materials flows, to be used by planners and decision-makers aiming at development towards sustainability.

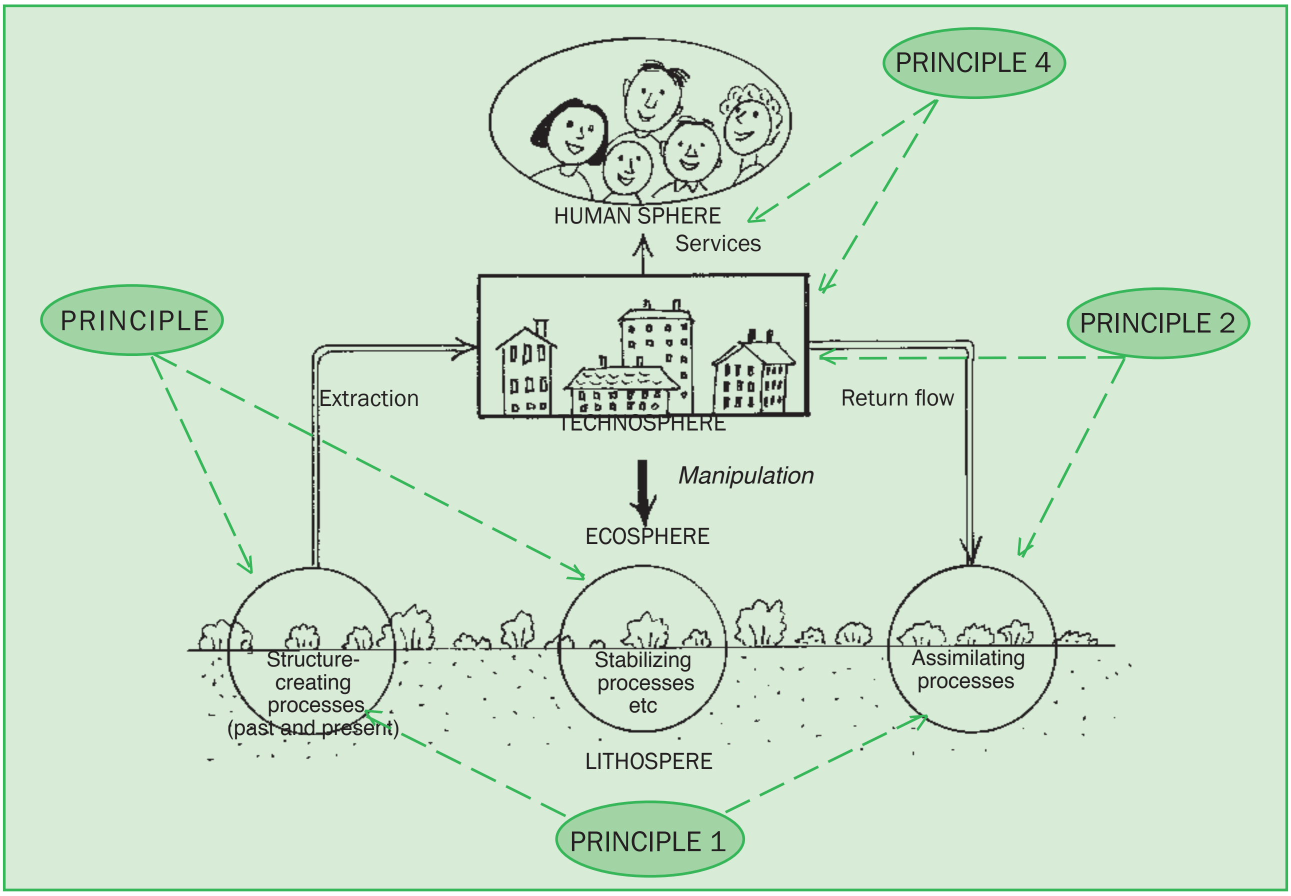


Figure 4.2 The foci of the socio-ecological principles, compare Fig. 2.3. (From Holmberg et al. [1994].)

It is no longer enough to focus on waste handling and emission control and be left with making the best possible use of whatever is discarded from the technosphere. We must produce an overriding materials strategy involving all the important parts of societal mobilizations and turnover of materials. We need to turn from a waste management strategy to a materials management strategy.

be fulfilled in order to achieve a sustainable interaction between society and nature. The first principle deals with the flow and use of substances from the lithosphere and the second with flows of substances that are produced within society. The third principle deals with the extraction of resources from the ecosphere and the manipulation of the ecosphere and, finally, the fourth principle deals with the metabolism and resources use within society. (Figure 4.2 shows the foci of the principles in relation to the society-nature interactions depicted in Figure 2.3)

These principles operation-alize the concept of sustainability as it was presented in the Brundtland report. They can be viewed as a more elaborate definition of sustainability and, as such, they can serve as a platform for discussions on sustainability issues, to be used in planning processes and in the formulation of policies at various levels of society. Practical experience from Swedish companies and local authorities has shown that the socio-ecological principles function well when making strategic decisions. More than 40 Swedish municipalities and 20 larger Swedish companies use these principles in their strategic planning process [Robèrt 1994, Holm-berg et al. 1994].

4.2 Principles 1 and 2 Turnover in balance

Principle 1 means that substances from the lithosphere must not be spread in the eco-sphere faster than various processes, for example, sedimentation processes, withdraw them from the ecosphere and return them to the lithosphere. If the input to the ecosphere (from the lithosphere and the technosphere) exceeds the sedimentation processes, these substances will accumulate in the ecosphere. Because of the complexity and delay mechanisms of chemical and physical processes in the ecosphere, it is often hard to say at what level of concentration such substances cause an environmental effect. In fact, every substance has its limit (often unknown) above which it will cause damage in various parts of the ecosphere.

For many chemical elements, anthropogenic weathering (mining) exceeds natural weathering. Even if materials extracted from the lithosphere by mining do not directly enter the ecosphere, there is continuous leakage of elements, for example, metals, from the accumulated pool in the technosphere.

Besides metals, there are other lithospherical substances that cause large environmental problems. Compared with that of today, a radically decreased use of fossil fuels is necessary in order not to accumulate too much of the greenhouse gas carbon dioxide in the atmosphere. This accumulation has led to that the concentration of carbon dioxide in the atmosphere has increased by 30%. Acidification is another consequence of the extensive burning of fossil fuels. Society has more than doubled the flows of SO_2 in the ecosphere. The uranium that is used by the nuclear industry causes risks and damage connected with mining waste, enrichment waste, use in reactors and the management of spent fuel as waste.

The second principle means that substances must not be produced faster than they can be broken down and integrated into biogeochemical cycles or deposited in final deposits in the lithosphere. Otherwise such substances will accumulate somewhere in the ecosphere and the concentration will increase towards limits (often unknown) at which damage starts to occur.

Fulfilling this principle will lead to decreased intentional and unintentional production of natural substances that can accumulate, such as, the production of nitric oxides in combustion processes. The assimilation capacity of the ecosphere is often smaller for persistent substances foreign to nature (for example, DDT) than for substances that exist in nature, because the ecosphere has never adapted to those new substances. Their persistence implies that, after being used, they accumulate in the ecosphere if they are not destroyed within the technosphere. Thus, continued production of such substances cannot be allowed. In practical terms this means that we have to phase out the use of such compounds completely.

4.3 Principles 3 and 4 Using the earth carefully

Principle 3 implies that society must not systematically reduce the physical conditions for production capacity in the ecosphere or the diversity of the biosphere. Society must neither take more resources from the ecosphere than are regenerated, nor reduce natural productivity or diversity by manipulating natural systems.

Our health and prosperity depend on the capacity of nature to reconcentrate and restructure used materials into resources. Society is dependent on the long-term functions of ecosystems. Even if Principles 1 and 2 are fulfilled, society must be careful in its manipulation of the resources base not to lose the productive capacity to supply food, raw materials and fuel. This dependence will become more obvious when the use of fossil fuels and uranium is reduced (according to Principles 1 and 2).

The principle implies a more efficient and careful use of productive areas in agriculture, forestry and fishing and more careful planning of infrastructure.

There is a close connection between soil and vegetation. The quality of soil is often more fundamental than the production of the vegetation on it since soil is more difficult to restore. Vegetation can often be reintroduced if the production capacity of the soil is not damaged and if the specific species are not extinct. It is usually considerably harder to restore eroded slopes (for example in the Mediterranean region) or salinated soils (for example by the Aral Sea). Society's manipulation of land areas also often affects the supply of fresh water. Manipulation of land can decrease natural refilling. It is therefore important to have a balance between extraction from a water reservoir and its natural refilling.

Besides the requirement of production capacity not being systematically reduced, it is important to preserve the stability of the ecosphere. High biodiversity is, as already mentioned, an important factor in preserving the stabilizing functions of the ecosphere. The term 'biodiversity' can be used to summarize three types of biological variation: (i) genetical variation within a specific species, (ii) the number of species within an ecosystem and (iii) the variation of ecosystems (biotopes) within a geographical area.

Principle 4 means that basic human needs must be met with as small an impact on the ecosphere as possible.

Principles 1, 2 and 3 constitute the external conditions for the sustainable metabolism of society. Assimilation capacity as well as the available resources flows are limited. In order to fulfil human needs for a growing global population, the resources and services obtained from nature must be used efficiently within society. Socially, efficiency means that resources should be used where they are needed most. This leads to the requirement of a just distribution of resources among human societies and human beings, within the present generation and between the present generation and future generations. (For a more thorough discussion, we refer to Holmberg et al.1994.)

To achieve this we shall need to increase technical and organizational efficiency in the global society and introduce a more equitable resource distribution including more resource-efficient life-styles in the rich part of the world.

4.4 Adapting materials flows

The flows of materials associated with industrialized society are necessary components in the process of creating services for people. Today, these flows are too large and involve too many harmful substances if there is to be development towards sustain-ability. The total impact of these flows on nature reflects the unsustainable use of materials today and is seen, for example, in increased global warming, depletion of the ozone layer, increasing metal concentration in soil, rapidly decreasing rain forest areas and destruction of land in connection with mining. How can we decrease the environmental impact of materials use at the same time as maintaining the services that are provided by the flows and transformation of materials?

The box below explains how the 'sustainability equation' expresses the impact on nature as a product of four anthropogenic factors, that is, four factors that to some extent can be controlled by society. This equation can be used as a starting-point when discussing ways for approaching sustainable materials flows.

The 'sustainability equation'

The impact on nature is given as a product of four anthropogenic factors.

Given the population and development goals in the form of global industrialisation, the means to decrease the impact on nature to a sustainable level are dematerialization and transmaterialization of the societal exchange of materials with nature. (There have been various combinations of factors used in this type of equation which goes back (at least) to the seventies.)

The impact I is a vector in which each component quantifies a certain kind of environmental impact, for example, radiative forcing, that is, an energy imbalance leading to a climate change. On the right-hand side, this impact is decomposed into the four 'factors'. (Bold style indicates a vector and underlined bold indicates a matrix.):

- the matrix $\underline{i}$ with components reflecting impact per unit of materials and energy flow,

  $$\underline{i} = \frac{\text{impact}}{\text{material \& energy flow}}$$

- the vector m describing the size of different flows per service unit,

  $$m = \frac{\text{material \& energy flow}}{\text{utility or service}}$$

- the utility per capita u, and

  $$u = \frac{\text{utility or service}}{\text{capita}}$$

- the global population level P

  P = population

Impact on Nature: $I = \underline{i} \times m \times u \times P$

Corresponding change or state:	transmaterialization	dematerialization	wealthy society	10^{10}
	Mean	Mean	Goal	Given

SUSTAINABLE **DEVELOPMENT**

The factor representing world population, P, is more or less given during the next fifty years. Even an immediate reduction in the birth rate to the reproduction level around two children per family, will, due to the inherent growth momentum in today's population, lead to around 8 billion people in the middle of the next century. Around 10 billion people in 2050 is a central projection in United Nations global population estimates. For the Baltic region today around 85 million people and Europe, no significant increase in the population is expected. Population growth elsewhere may lead to large-scale immigration from other parts of the world or expectations about sharing of resources through, for example, increased exports of food.

If we assume as one goal for development that the use of resources within society must be efficient and just in order to meet human needs, we get a lower limit for the factor that represents the utility per capita (u). Today there are large differences in utility per capita between different countries and between peoples within the same country.

Even if it could be argued that we in the developed countries are (materially) wealthy enough, there are strong demands to increase the average global level of service or utility per capita, to reach a higher standard of living in the developing world.

Besides the goal of increasing utility per capita within the present generation, there is also the goal of making it possible to have a high level of utility per capita in the future– the per capita goal is a question of both intra- and intergenerational justice.

The limitations of litho-spheric resources put physical restrictions on the possibility of using different materials in the future, for example, the accumulated use of lead in Sweden since 1880 has been about 300 kg/capita. If we compare this figure with what is left in global reserves, namely, 10 kg/capita and the maximum estimate of global resources that can be used in future, namely, 250 kg/capita, it is clear that the Swedish way of using lead over the last century cannot be realized on a global scale in the future.

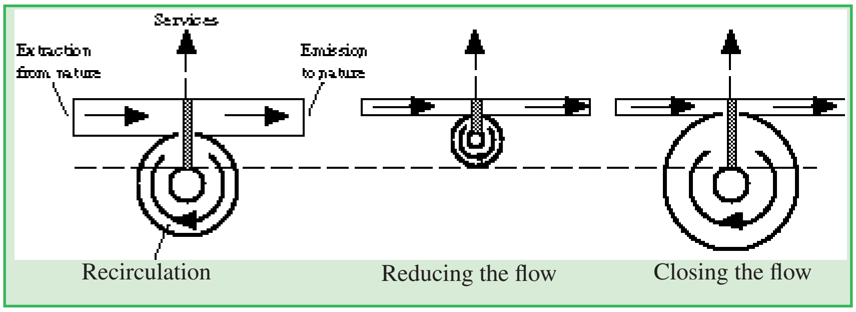


Figure 4.3 Dematerialization can be accomplished in two principal ways: less materials flow to achieve a certain service (reducing the flow) or increased recycling of materials (closing the flow).

Further industrialisation of the world and an increasing standard of living, measured as increased economic activity and production of service per capita, as well as the expected increase in the global population to around 10 billion people during the next century will thus lead to an enhanced demand for services from material flows.

The simple equation illustrates the dilemma facing humankind – the double challenge inherent in the concept of sustainable development: on the one hand, to develop and reach an acceptable service level from materials/energy flows for a growing population while, on the other, being able to decrease society's harmful physical influence on nature.

4.5 The solutions – reducing the flow or closing the flow

One solution to this dilemma is to be found in the last two factors in the equation, m and i. Concerning world-wide societal flows of materials, one can identify two main strategies for decreasing the environmental impact of materials flows, corresponding to changes in these two factors — *dematerialization*, that is, more service out of a certain exchange of materials with nature, and *transmaterialization*, that is, substitution of materials flows with less harmful impact for more detrimental ones.

Dematerialization can be accomplished in two principal ways: less materials flow to achieve a certain service (reducing the flow) or increased recycling of materials (closing the flow), see Fig. 4.3.

Reducing the flow implies more efficient use of a given material for a given function.

Copper wire in power transmission is one example of dematerialization. By raising the transmission voltage it has been possible to reduce the amount of copper needed to transmit a given amount of electricity. Another example is the large reduction of the silver content in a roll of film.

By increasing the quality of a material, such as the strength of a metal, materials requirements can be reduced. It has been estimated that the Eiffel tower in Paris today could be built with one seventh of the steel content. This possible reduction in iron use is, however, partly achieved by alloying the iron with small amounts of other elements. In the electronics industry we can see an ongoing *miniaturization* of electronic components as with silicon chips, which can reduce the need for a given material for a given function.

Multifunctional use of products offers another opportunity for reducing the need for materials for a given function. For example, a roof-mounted solar collector can also function as roofing.

By making the *products last longer* the same amount of materials can provide services for longer and therefore the amount of materials for a given service can be reduced. This can be achieved in many ways. For example, we can increase the quality of the materials or components involved. Materials can be protected from wear or corrosion. Repairability, for example through a modular construction, may be possible to increase.

4.6 Recycling

Closing the flow of materials within society implies that the same asset or material is used again and again. Cycles can be closed at various levels. We can *reuse* goods; for example, glass bottles for packaging can be refilled. Materials in goods can be *recycled* as with, for example, the metal in aluminium cans or the lead in lead-acid batteries. The closure can be within production processes, where manufacturing waste is fed back into earlier material-processing steps.

In some cases this is already well developed for waste generated early in the production chain, as with copper scrap in the manufacturing of copper wires. However the challenge is to close material flows for complex consumer products. For many materials (for example, toxic and/or scarce materials) it is important that dissipative use, that is use that leads to unavoidable losses of materials is avoided. But, of course, depending on the process, the dissipation is more or less inherent and thus more or less difficult to avoid without more radical changes: For instance, the by-flow of lead additives in petrol may be relatively easily substituted, but it is harder to avoid the dissipation of the petrol itself when used as a fuel.

The quality aspects of recycled material are very important. An important condition for the successful recycling of materials is that flows are sufficiently pure or separable. Unnecessary *mixing* of different kinds of materials can destroy this and should therefore be avoided. The effects of the inevitable loss of quality in materials can be minimized through a *cascading use*, where each step involves a drop in quality requirements. After each recycling step of a certain material, it should be used in such a way that the quality can be kept at the highest possible level.

One challenge is to achieve a high proportion of *true recycling* that is recycling of the material to the same use once again. There are three main qualities that are interesting:

- purity,
- structure and
- exergy.

For instance a special steel should not be used as reinforcing iron after only one cycle if the *purity* is to be saved. The bulk *structure* of wood, for example, can be utilized, if wood is first used as a construction material, before its fibre structure is used in paper of stepwise declining quality and then its chemical structure is finally utilized in the chemical industry or for fuel production and combustion.

In the energy sector, one can also improve *exergy efficiency* through cascading use of energy, where each step involves a drop in temperature.

In this context Ayres & Ayres [1995] have discussed waste mining as a strategy which utilizes waste streams from (currently) irreplaceable resources, for example, recovering elemental sulphur from natural gas and petroleum refineries. This strategy reduces

(i) environmental damage due to the primary waste stream,

(ii) the rate of exhaustion of the second resource and

(iii) environmental damage due to mining the second resource.

4.7 Transmaterialization

Even if the use of a certain material is efficient in terms of delivered service per mass unit of the material, the impact on nature may still be unacceptable. In that case, transmaterialization may remove a more serious impact by a shift to a materials use that implies less environmental impact. Transmaterilization can be achieved by, for example, substituting less harmful and/or less scarce materials for hazardous and/or more scarce materials.

Substitution can be done at different technical levels in the system that delivers the services in question; see Table 4.1. The first two levels deal with society's choice of material resources. Levels three and four are connected with the choice of technology, levels five and six deal with organization and strategies and level seven is connected with the type of services we demand. Transmaterialization in the use of metals will be discussed in Chapter 7.

The amount and the type of services that we demand in the end have consequences for the use of resources. The use of services varies a lot despite the fact that fundamental human needs are the same in all cultures and in all periods of history. Max-Neef

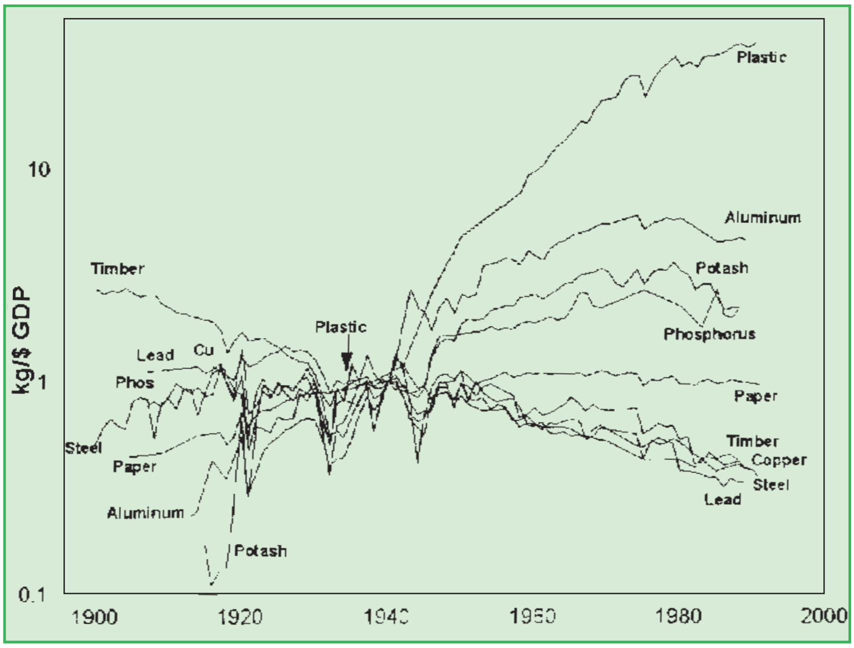


Figure 4.4. The intensity of materials use in the United States from 1900 to 1990. Production data (kg) divided by GNP in constant 1982 dollars. All materials are relative to the 1940 value [Wernick et al. 1996].

Materials management strategies

15 approaches to efficient materials management

I. REDUCING THE FLOW – USE LESS MATERIAL FOR A SERVICE

1. Use the material more efficiently

By raising the transmission voltage in a copper wire it is possible to reduce the amount of copper needed to transmit a certain current.

2. Increase the quality of the material

By increasing the strength of a metal, e.g. by using an alloy, less material can be used for the same purpose. It has been estimated that the Eiffel tower in Paris today could be built with one-seventh of the steel content it actually has.

3. Miniaturization – use a smaller equipment

By making equipment smaller, less material is used. Computers, now based on miniaturized electronic components, such as silicon chips, provide a dramatic example. A much smaller computer has the same functions as a large machine earlier.

4. Multi-functionality – Let the equipment serve several purposes

Multi-functional use of products offers another opportunity for reducing the need for materials for a given function. For example, a roof-mounted solar collector can also function as roofing.

II. SLOWING DOWN THE FLOW – MAKE THE MATERIAL LAST LONGER

5. Improve the quality to make the equipment last longer

By making products last longer, for example by increased quality, the same amount of materials can provide services for longer and therefore the amount of materials for a given service can be reduced.

6. Protect the material in the equipment better

Materials can be protected from wear or corrosion. Modern cars last much longer than earlier ones because of better protection of the surface.

7. Better maintenance

By regular maintenance and by using equipment that can be maintained properly, the equipment or material can be used longer.

8. Reparability – Make the equipment more easy to repair

Reparability, for example through the modular construction of equipment, will increase the longevity of the materials used.

Table 4.1. Levels of substitution [Månsson 1993, Holmberg et al. 1994].

Level of substitution	*Example*
1. The raw material level	The same material may be obtained from different raw materials with different environmental characteristics, e.g., hydrocarbons from biota or fossil fuels.
2. The material level	Aluminium can substitute for copper in electrical power transmission.
3. The component level	One type of battery may have better properties than one currently in use.
4. The sub-system level	Electric motors may at one time replace internal combustion engines for cars in local traffic.
5. The system level	Private cars may be largely replaced by trains for medium – and long-distance travelling.
6. The strategic level	Different strategies can lead to the same goal. If the goal is 'clean' environment, then there can be a shift in scientific strategy from environmental pathology to societal prophylaxis.
7. The value level	Cultural and individual values decide what strategy to choose. Moreover, if people want sustainable development, this will lead to consequences at all other levels.

III. CLOSING THE FLOW – USE THE MATERIAL AGAIN

9. Reuse the goods itself

Most goods or equipment are of course used more than once. In some instances a proper strategy is required to make this happen, as with glass bottles that may be refilled.

10. Recycle materials in production processes

Many different strategies are applicable in the industrial production process to reduce material intensity. This is part of waste management strategies. Thus manufacturing waste can be fed back into earlier material-processing steps, as when for example copper scrap in the manufacturing of copper wires is fed back into the process.

11. Recycle materials in consumer goods – true recycling

Materials in consumer goods may be recycled. This is particularly important for materials that are toxic, such as heavy metals, or materials that are expensive to produce, such as aluminium. Important cases are thus recycling of the metal in aluminium cans and the lead in lead-acid batteries. Recycling of the material to the same use once again is true recycling.

12. Cascading or down-cycling of materials

In many cases there is an inevitable loss of quality in material when it is used. However it may be apt for a different use requiring less quality. This is down-cycling or cascading. The typical example is paper where the fibres in the paper itself go through a wearing process, which limits the use to a few cycles. The chain might start with high-quality paper going to newspaper and then to cardboard paper. The chain or spiral ends when the material is used for energy production in combustion.

The refilling of bottles is a case of true recycling – the use of a material for the same purpose several times.

IV. SUBSTITUTE THE FLOW – USE A DIFFERENT, LESS HARMFUL, MATERIAL

13. Substitute a material for a less harmful one

Transmaterilization means that one material is exchanged for another. An important aspect is when a hazardous material is exchanged for a less harmful one. The exchange of mercury in a number of applications, from barometers to teeth repair, belongs to this category as does the exchange of many solvents used for painting.

14. Substitute a scarce material for a less scarce one

Sometimes it is important to find a less scarce material for a particular use. Substituting copper wires in telephone connections by fiberoptic cables is one example.

15. Substitute a non-renewable material for a renewable one

Non-renewable materials will eventually necessarily be exchanged for renewable ones. An important example is when fossil fuels are exchanged for renewable fuels, such as biomass. An important case is the exchange of petrol in cars for alcohol from biomass.

The replacement of the old, rather large, electric relay, containing considerable amounts of mercury, with modern devices illustrates several management prin-ciples: dematerialization by using a smaller size, sub-stitution of a harmful material for a less harmful one, and the need for less current when the modern relay is used.

[1986] considers those needs to be few and classifiable.

He suggests the following classification: permanence (or subsistence), protection, affection, understanding, participation, leisure, creation, identity (or meaning) and freedom. What changes, both over time and between cultures, is not the needs but the forms or the means by which these needs are satisfied. Since many of the fundamental human needs are not directly associated with any large turnover of nat-ural resources, a plausible conclusion is that society can increase the fulfilment of those needs at the same time as it decreases its use of natural resources.

4.8 Managing future materials flows

Huge movements of materials are induced by the ongoing activities in modern societies. However, as pointed out earlier, materials are not used in themselves but contribute to providing a service. The services delivered, for example measured as the net or gross domestic product (NDP or GDP), have increased dramatically during the industrial era because of economic development, sustained by capital accumulation, technical development and increased skills. This has been followed by an increase in the total use and movements of materials.

Technological development has also made it possible to get more service out of less materials. The mean value added to materials in the production system has successively increased. But at the same time new and more efficient methods have also meant that many materials have become cheaper. Materials use intensity showed a general tendency to increase at the beginning of industrialization but then to level out and decrease. This is especially true for some of the 'old' high-volume materials in society such as iron, cement and lead.

But part of the explanation is transmaterialization: substitution with 'new' materials has contributed to the decrease in intensity of the use of old materials. For new materials, like aluminium and plastics, which have come into common use during the last fifty years, there is still an increasing tendency in materials use intensity; see Figure 4.4. Today in some countries, for example, the use of plastics by volume is larger than all metals together. In the manufacturing of goods, plastics to a large extent have substituted for various metals.

Huge material flows are connected with accumulation of infrastructure, the use of fossil fuels and the linear flows of metals. Halting these tendencies, stopping the expansion of the infrastructure, phasing out fossil fuels and efficient recycling of metals will create a dramatic change and a reduction in materials flows and the rucksacks.

But this will not solve all problems. There will still in society be flows of hazardous materials which will require careful transmaterialization to less harmful alternatives. The pressure on biomass resources will increase and with it the necessity to have more stringent handling of important nutrients. New technologies or other solutions may solve the environmental and resources problems connected with certain materials flows but also, in parallel, introduce demands for new materials, possibly giving rise to new problems. It is thus important to substitute in a direction leading towards an overall more sustainable materials flow.

To be able to achieve the necessary radical decrease in the long-term environmental impact and resources exhaustion resulting from the present practice of materials use, we shall certainly need more control over societal materials flows.

To which extent the means to implement such a strategy can rely on tendencies, mechanisms and institutions already present in society or imply new more radical measures is another question. But probably these means have to differ between various materials or group of materials. The characteristics of materials, the amounts mobilized and their rôle and through-flow in society as well as their turnover in nature vary considerably, depending on which materials we are focusing on. On pages 28-29 we have tried to summarize some important characteristics for major groups of materials used in society. We have also depicted some possibly important components or central solutions necessary for adoption in materials management strategies aiming towards sustainability.

The production and use of various goods and services will be subordinated to this strategy. We shall thus need a careful mixture of dematerialization and trans-materialization measures to get rid of or decrease what we do not want to rely on and to handle in an acceptable way what we decide to keep. On the way, however, there will be many conflicting goals and choices to be made between different means of achieving more sustainable practices. Questions to resolve may be, for example:

- within agriculture, will more intensive use on limited areas with more control or more extensive use (closer to natural) over larger areas, be the better practice?
- for metals, how can the choice be made between dematerialization and transmateriali-zation depending on the metal, available technology and the characteristics of the various uses?
- for energy and transportation technologies, to what extent will resources restrictions hinder efficiency improvements and the phasing out of fossil fuels?
- to what extent is it possible to make use of overburden, slag and other rucksacks in the infrastructure instead of discarding them?

5.

THE UNBALANCED CARBON CYCLE — A GLOBAL PROBLEM

by Christian Azar and Göran Berndes

Carbon – the life atom

Human activities have substantially altered both pools and flows in the natural carbon cycle. Combustion of fossil carbon and deforestation are the main causes for the 30 per cent increase in atmospheric CO_2 concentrations. A continued increase is expected to cause significant climatic changes. In this chapter, we review the present use of carbon in its various forms. We also discuss the use of carbon in a future global industrial and materially wealthy society of ten billion people. This exercise highlights various features that need consideration when discussing the societal metabolism of a future sustainable society, in terms of utilisation of fossil carbon and biospheric carbon.

5.1 Societal use of carbon today

For food and many materials, human society still completely depends on products of photosynthesis and, until the middle of the 19th century, biomass also dominated global energy supply. Although fossil fuels have taken over as the dominant source of energy, biomass still accounts for more than 10 per cent of global primary energy supply and is widely used in developing countries.

Approximately 75 per cent of the global energy supply is based on fossil fuels, namely, coal, oil and natural gas. Combustion of both fossil and biomass carbon gives rise to CO_2 emissions but emissions from biomass burning are recaptured by plants if they are regrown. Thus, biomass has the potential to be a CO_2-neutral energy technology. At present, combustion of fossil fuels give rise to emissions of 6.0 Gton C/year and land-use changes, mainly deforestation of tropical rain forests, give rise to an additional 1-2 Gton C/year.

The use of fossil carbon is around ten times larger than the total use of all metals in society. It is also worth noting that fossil fuels contain vast quantities of heavy metals and other elements. Flows of elements associated with the extraction of fossil fuels are actually greater than the amounts that are mined for several elements, for example, aluminum (Al), vanadium (V), lithium (Li), gallium (Ga), beryllium (Be), mercury (Hg), silicon (Si), germanium (Ge), sulphur (S) and selenium (Se). [Azar *et al* 1996]

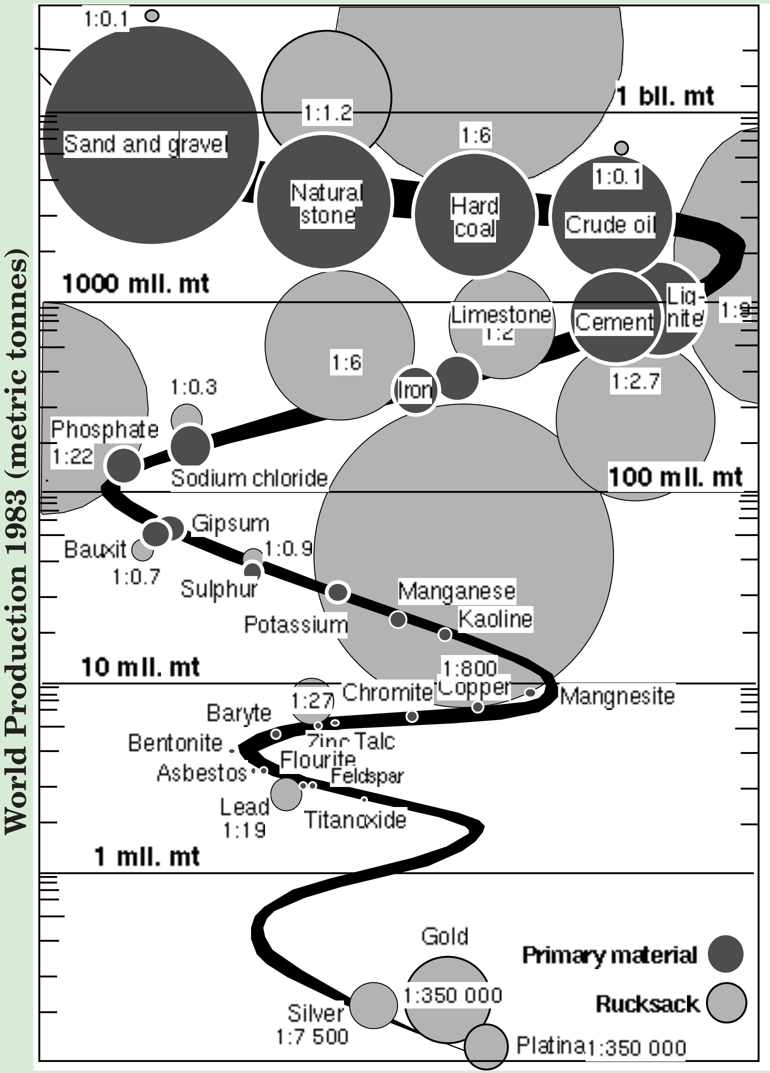
Fossil carbon is also used to produce plastics and other organic chemicals, for example, lubrication oils, solvents and printing inks. When eventually broken down these will also give rise to emissions of CO2. In addition, some specific industrial processes give rise to net emissions of CO2. Changing the production process may eliminate all greenhouse gases associated with a certain industrial operation. Although, there are some cases where the release of greenhouse gases is intrinsic to the product, making materials substitution is the only option for reduction of greenhouse gases. Cement production is one such example, where process-related emissions contribute 40 per cent of total emissions of lithospheric CO2 to the atmosphere (in calcination CO2 is driven off from the carbonates). This means that they are much lower than energy-related emissions but, in a future global industrialized society, these emissions alone may reach a rate which is high enough to cause atmospheric concentrations to continue to increase even if emissions from the energy sector are phased out.

Societal use of biomass and fossil fuels also leads to unintentional emissions of carbon in the form of methane. Emissions originate from leakage of natural gas, coal mining, biological processes in oxygen-poor environments such as rice paddies and digestion by ruminants. Global anthropogenic emissions are around 0.4 Gton/year, which is more than twice the natural rate of methane emissions.

5.2 Use of carbon in a ten-billion-people industrialized society

Figure 5.1 illustrates the present global supply of biomass and fossil carbon for food, materials and energy. We have also included an estimate of the future supply requirement of biomass and fossil carbon for food and materials in a future industrialized society of 10 billion people. In this estimate, we assume a future global average per capita material standard at the same level as in the present industrialized countries (see Table 5.1).

However, the future form of society that is the basis for our calculations is not a replica of the industrialized world of today. Technological progress leads to improvements in efficiency in the



The main materials flows – chapters 5, 6 and 7

Global material turnover, as described in the accompanying logarithmic diagram from the Wuppertal Institute (see also Fig. 3.2), is dominated by a few categories. At the top of the diagram we find black coal, lignite and oil and, in even larger amounts, their ecological rucksacks. All these turnovers represent the extraction of fossil fuels; all of them contribute to large-scale manipulation of the natural carbon cycle. The carbon cycle is discussed in chapter 5.

The flows of the bulk materials, sand and gravel, are even larger but have small rucksacks and certainly not the same environmental impact.

High up in the diagram are also found phosphate, calcium carbonate, used in cement, and sulphur. All of these, together with nitrogen, belong to the category of macronutrients, as they are in comparatively large amounts needed for plant growth. The large-scale impact on the flows of these substances also has very destructive consequences, such as eutrophication and acidification. The turn-over of these substances is dealt with in chapter 6.

Finally there are the metals. Only a few of them are in the upper part of the diagram: iron, aluminium (from bauxite) and copper. Further down is a series of metals used for special purposes. The weight of the rucksacks of these is often very large. For copper it is about 800 times larger than the metal itself and the mining of copper is both destructive and expensive. The turnover of metals is discussed in chapter 7.

All the materials mentioned are today entirely or largely extracted from non-renewable resources. The creation of a sustainable society will require that the turnover of materials is reduced considerably, that renewable resources are used and that the ecological rucksacks are minimized.

use of energy and other resources. Construction of basic infrastructure is one of the most materials-intensive activities in an industrialized society. A more mature industrialized society, characterized by maintenance rather than build-up of infrastructure, can be assumed to require fewer materials. For example, we have assumed the global average per capita use of cement to be 280 kg/year. In 1988 the use of cement in the OECD countries was around 470 kg and the use in the former USSR and eastern Europe was only slightly lower.

Figure 5.1 clearly shows that, even though efficiency in materials turnover is assumed to be much higher, the future requirement for food and materials will be much larger than today because of population growth and an assumed higher global average standard of living. The assumed future supply of biomass for food and materials means nearly a three-fold increase compared with now. Therefore, the supply requirement for food and materials alone, will substantially add to the increased human appropriation of global biomass production.

Total energy use in a future industrialized society can only be guessed but it will most certainly be much higher than global energy use today. High efficiency scenarios project future total energy use by 10 billion people to be two or three times the present level.

For example, global energy use in 1990 was approximately 385 EJ (primary energy). Doubling this global energy use would correspond to the energy content in over 38 billion tonnes of biomass, or slightly over 17 Gton/year in terms of biospheric carbon. By-products and residues from the food and materials sectors may be used as an energy source but the major amount of biomass energy will have to come from plantations dedicated to energy crops. [Halb *et al* 1993]. A comparison with the extent of biomass used for food and organic materials today (Figure 5.1) reveals that if biomass for energy would evolve as a significant contributor to global energy supply, the establishment plantations of energy crops would emerge as a new form of anthropogenic land use that is comparable in scale to that for agriculture and forestry.

Therefore, the crucial question is: what are the prospects for utilizing carbon in the future supply of energy through the continued use of fossil carbon, and the expanded use of biomass energy?

5.3 Restrictions on fossil fuels

The risk of substantial and rapid climatic changes has pushed governments all over the world to negotiate and sign a climate treaty, the United Nations Frame-work Convention on Climate Change. The main objective of the convention is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system". Greenhouse gases are gases that have the ability to change the radiative balance of the atmosphere and the most important anthropogenic greenhouse gas is CO_2.

There is no agreement about the level we would need to stabilize at in order to reach this objective. In Table 5.2, we present estimates of the possible accumulated emissions we may emit over the next century in order to stabilize at various atmospheric concentrations.

The Stockholm Environment Institute [SEI, 1990] considers 2^{o}C as a high-risk temperature change and, if we would choose to follow their recommendation, we may need to stabilize atmospheric concentrations of CO_2 at 420 ppmv (a temperature sensitivity of 2.5^{o}C for a doubling of the CO_2 equivalent, and once again assuming 1W/m^2 from other greenhouse gases). As a rough estimate, this would give us an 'emission space' of 5.6 Gton C/year over the next century. The SEI also suggests 0.1^{o}C/decade as a maximum rate of change and this would even further sharpen the restrictions on CO_2. Assuming a high climate sensitivity, stabilization has to be carried out at 325 ppmv, that is, a much lower level than at present and this target would require that global emissions over the next century are kept below 2.5 Gton C/year.

Looking even further ahead, emissions must drop substantially below the level possible over the coming century, whatever stabilization level we choose to opt for. It has been estimated that stabilization at or below 500 ppmv would require emissions to be as low as 0.2 Gton C/year (this calculation assumes no net long-run changes in the stock of carbon stored in biomass on land).

This means that in a very long-term perspective, from 2100 onwards, even plastics must be made from other materials, that is, biomass. This would also add to the demand for biomass from our bioproductive lands. Also cement production would, in our assumed ten billion people industrialized society, give rise to emissions that exceed the 0.2 Gton C/year limit.

Finally, it should be noted that it is possible to sequester CO_2 emissions from fossil fuels. This can be done either by decarbonizing flue gas from stationary combustion plants or by decarbonizing the fuel itself by converting it to hydrogen. However, there are still a number of unsolved questions related to the final storage of the sequestered CO_2.

5.4 Restrictions on biomass use – global productivity

So what are the prospects of providing a doubled global population, living at a material standard of living comparable to that of a typical industrialized country, with biomass for food, materials and potentially also energy, while at the same time managing land in an environmentally sound way, for example, managing biodiversity and the soil's long-term bioproductivity in a proper way.

Global net primary productivity (NPP), can be used as an order-of-magnitude estimate of the potential for human biomass appropriation. Estimates of global NPP are scattered within a wide range but 40–60 Gton C/year for the continents and 20–30 Gton C/year for the oceans could be seen as central ranges. [Ajaty *et al* 1979] To give information about how much biomass is available for harvesting, NPP must be reduced by the amount used in hetereotrophic respiration. By subtracting from NPP total litter-fall, that is, the flux from living to dead matter, a rough estimate of annual biomass increment can be made.

Starting with terrestrial productivity, global annual biomass increment in all forests, grasslands and croplands taken together, can be estimated at almost 14 Gton C/year. Of course, an estimate of this kind suffers from uncertainties of underlying estimates of NPP and litter-fall. Underground growth (roots) should be excluded when estimating appropriable biomass increment. On the other hand, the estimate is valid only for the structure and extent of *present* ecosystems. The amount of NPP that goes to appropriable biomass increment may be significantly increased by transforming present ecosystems,

Table 5.1 Average food, organic materials and cement end-uses in a typical industrialized society

Food	GJ/cap·yr
Vegetable products	3.5
Animal products	1.5 a)
Organic materials	**kg dry matter/cap·yr**
Paper & paperboard	150
Sawn wood & wood panels	190
Textiles	20
Other materials & chemicals based on wood	50
Plastics (petroleum base)	70
Other materials & chemicals based on petroleum	100
Cement b)	**(kg/cap·yr)**
	470

a) The supply requirement is substantially higher than 1.5 GJ since there are energy losses when converting animal feed into animal products.

b) Globally, the calcination process gives rise to a total of 0.17 Gton C/year emitted to the atmosphere.

Source: Karlsson et al 1996.

for example, by substituting forests and grasslands with short-rotation tree crops.

Total respiration (autotrophic + heterotrophic) rises with the maturity and complexity of ecosystems and, in a fully mature (climax) ecosystem, total respiration would equal gross primary productivity, making biomass increment zero. Human-managed ecosystems are harvested before reaching a climax state and therefore respiration stays lower than gross primary productivity.

Thus, this calculation only gives an order-of magnitude-estimate of how much land biomass can be harvested. Nevertheless, a comparison with the earlier estimates of societal requirements in fig. 5.1 reveals that these are indeed smaller, but seem to be of the same scale as the global appropriable land biomass increment.

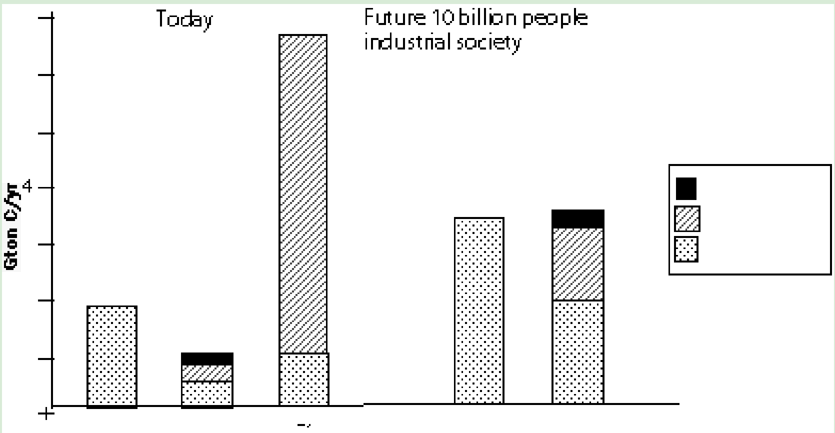


Figure 5.1 Present global supply of biomass and fossil carbon for food, materials and energy. Also shown is a scenario for the supply requirement of biomass and fossil carbon for food and materials in a future industrialized society of 10 billion people.
The emissions of fossil carbon to the atmosphere coming from calcination in cement production is included explicitly in the materials sector.

5.5 Cultivating the seas

Turning to aquatic productivity, the situation is quite different. Plankton commonly accounts for more than 80–90 per cent of the ocean's NPP. Comparing marine NPP with the annual fishing harvest verifies that, given the present practice of harvesting aquatic productivity, only a very small fraction of aquatic NPP is available for human use (fish catches amount to 0.02 Gton C/year). In a way, fishing can be said to correspond to gathering and hunting, a practice that ceased to be the main strategy for harvesting terrestrial productivity more than ten thousand years ago. The expansion of fish aquaculture, that claims to have the potential to provide a significant proportion of the global fish supply, would then correspond to animal husbandry and pasture farming. The strategy of harvesting at a high trophic level limits the proportion of aquatic NPP that is appropriable. The aquatic analogy to crop production would be plant aquaculture. One example of plant aquaculture is production of water hyacinths, which are utilised for pig feed, fertilizer and the production of fuel (methane).

Today, the proportion of the total societal biomass harvest coming from aquatic resources is very small. Fish is an important source of protein in the diet, especially in many developing countries, but its contribution in terms of food energy (or carbon) is almost negligible. Furthermore, many signs indicate that fish catches are at, or beyond, the limit in most areas. This means that the proportion of fish in the global diet will probably decrease, even if a dramatic expansion of fish aquaculture were to take place.

The possibility of an expansion of plant aquaculture large enough to contribute significantly to the

Table 5.2 Stabilization scenarios. Accumulated emissions if stabilization at various levels of CO_2 in atmosphere is to be achieved.

Concentration of CO_2	Expected temperature change[a)] (degr. centigrades)	Accumulated emissions 1990–2100 (Gton C)	Average emissions 1990–2100 (Gton C/yr)
350 ppmv	0.8–2.5	300–430	2.7–3.9
450 ppmv	1.4–4.1	640–800	5.8–7.3
550 ppmv	1.8–5.4	880–1060	8.0–9.6
650 ppmv	2.1–6.4	1000–1240	9.1–11.3
750 ppmv	2.4–7.3	1220–1420	11.1–12.9

[a)] The expected temperature change range is based on IPCC's best estimate range of 1.5–4.5°C for a CO_2 equivalent doubling. We have also included an assumed 1 W/m^2 radiative forcing from other greenhouse gases. No aerosols were assumed since these are expected to be phased out for other environmental reasons. The pre-industrial concentration of CO_2 was around 280 ppmv.

Source: IPCC, 1995.

global biomass harvest is difficult to estimate. Therefore, continued discussion in this chapter about prospects for human appropriation of the global biomass production will focus on terrestrial ecosystems.

Figure 5.2 The global population is expected to increase to at least 10 billion next century. India has a very fast growing population with more than 800 million. However their resource use is limited.

5.6 Bringing more land into practice

Basically, there are two options for increasing the overall production of biomass for food, materials and energy:

(i) bring more land under management practices, and

(ii) increase the harvest of biomass per unit of land managed.

Total land area on the Earth is a little over 13 billion hectares (Gha). In the absence of human interference, a large part of the Earth would have been covered with forests but over the last couple of centuries, a large-scale transformation of the Earth's surface has been carried out. Since the beginning of the eighteenth century almost 20 per cent of the world's forests and woodlands have disappeared. During the same period, agriculture has expanded dramatically: croplands have increased by more than 450 per cent and pastures have expanded into natural grasslands and forests. In densely populated industrialized countries most forests are artificial.

Various constraints make a large part of the world's land area unsuitable for crop production. 70–80% of the land area of the world is either ice covered, too cold, too dry, too steep, too shallow, too wet or too poor to support cultivation. At present 1.5 Gha are used for production of food or feed crops and it has been estimated that the total land area that could be dedicated to crop production lies in the range 2.7 to 4 Gha. [Alexandrates, 1995]. An additional 3 to 4 Gha would support grazing. At present, 4 Gha of the planet is covered with forests.

Although the total potential for expansion of croplands seems to be high, there are limits. The productivity of potentially cultivable land is variable and most of it has a moderate or low productive capacity because, in most countries, the best land has already been reclaimed. As much as around 70 per cent of potentially arable land is affected by one or more terrain and/or soil constraints such as steep slopes or sandy soil and a large part should preferably be left under natural vegetative cover.

Cultivating more land increases the risk of erosion and soil degradation because the natural vegetation protects the soil structure better. This notion also applies to grazing: too-intensive management leads to overgraz-ing which, in turn, leads to severe losses of vegetative cover and land degradation. Thus, in addition to the ecological impact of the progressive replacement of natural vegetation by intensively managed arable land and pasture, much newly reclaimed land is needed to compensate for losses due to erosion, salinization and other aspects of land degradation triggered by improper land use practice. Halting degradation of agricultural land and reclamation of already abandoned degraded lands for resumed agricultural production is a very important issue on the global agriculture agenda.

Furthermore, not all potentially arable land should be considered as available for agriculture. Expansion of land devoted to human settlements and infrastructure often leads to losses of bioproductive land. This process is likely to continue since both global population and per capita income are expected to grow.

When assessing the potential for harvesting forests for wood, one must take into account that a significant part of forest area may be considered unexploitable, for example, where wood-harvesting is limited by legal, economic or technical restrictions or where physical productivity is too low or harvesting costs are too high to make harvesting commercially feasible. It is also important to distinguish between various types of forest such as temperate and tropical forests, since their potential for wood extraction differs significantly. Biodiversity aspects also need to be considered.

In conclusion, more land is likely to be dedicated to crop production and animal grazing but with part of this being at the

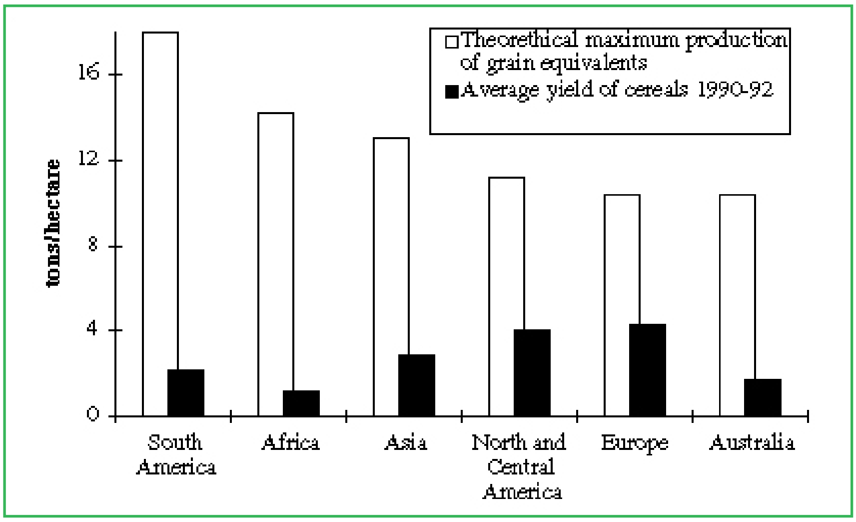


Figure 5.3. Theoretical maximum potential yields on the different continents, expressed in terms of grain equivalents, compared to average yields of grains obtained in 1990–92. Based on Plucknet et al 1993, and World Resource Institute 1994.

expense of forest land. More natural forest land will be put under commercial forest management practice.

5.7 Potential for in-creased productivity

With information about photosynthetic efficiency, soil and climate conditions, it is possible to estimate the theoretically maximum potential yield of specific crops. Although a purely theoretical exercise, such estimates can serve as a yardstick by which present yields can be compared to their theoretical potential. Such a comparison is made in Figure 5.3. As can be seen, Europe is the continent with the highest actual yields, despite the fact that the maximum potential yield is much higher in other regions. This can be seen as an illustration of the high-technology approach in European agriculture.

Figure 5.3 illustrates the huge potential for increased agricultural production that actually exists and also points out one key issue in world agriculture: the importance of the transition in non-industrialized countries from traditional agriculture, relying on land expansion for increased overall production, towards modern agriculture where higher yields are the main source of increased overall production.

If all continents of the world on average reached European yield levels, rather than what is theoretically possible, the same amount of land that in 1990–92 produced less than 2,000 million tonnes of cereal would instead deliver more than 3,500 million tonnes. In other words: *The global agricultural cereal output would increase by 75 per cent without any expansion of land dedicated to crop production!* In particular, South America, Africa and Asia would experience an enormous growth in total cereal production relative to what is achieved on these continents today.

It is important not to underestimate the huge input that is needed to reach the European fraction of the theoretical output on a global scale. Possible restrictions on vital agricultural inputs, such as water, might pose serious obstacles to yield increases in different regions. Careful regional assessments are therefore needed to understand better the prospects for productivity gains over the world.

Similarly, there is potential for increasing yields from forest lands. However, it is not yet possible to estimate the yields from future sustainable forestry that does not violate biodiversity constraints, in particular in tropical regions.

In tropical countries, forest plantations on already deforested land are expected to contribute to the future global tropical wood supply. Over the next couple of decades, however, the major portion will have to come from selective timber extraction in natural forests.

5.8 Biomass energy

In conclusion, the limited potential for biomass, does not imply that biomass energy will be unimportant. First of all, biomass may very well play a dominant role in energy systems at a regional or national level. In several countries around the Baltic Sea, for example, Sweden and Finland, biomass does have the potential to be a major energy source.

Biomass may also play a very important role in the transient phase away from fossil fuels towards renewable fuels. One reason for this is that during this phase, say between now and 2030, the global population and the global per capita use of carbon could be much lower than the levels prescribed here. This means that there will be a larger space for biomass for energy purposes.

The second reason is that biomass energy technologies are more developed and much cheaper than direct conversion of solar energy, the technology which we expect to be the dominant energy source in a future sustainable society. In addition to this, biomass energy could also lead to other environmental and economic benefits, for example, by promoting initial reclamation of degraded land, rural industrialization and employment in developing countries or by providing an opportunity to phase out agricultural subsidies in industrialized countries.

6.

NUTRIENTS FLOWS AND ENVIRONMENTAL THREATS

6.1 The increased nitrogen flow

A major disturbance of the natural nitrogen flows comes from an intensification of the nitrogen cycle by increased fixation. Global fixation has increased by a factor of two or three; see Table 6.1. With the present excess fixation rate, the accumulated fixation over 50 to 100 years would correspond to the total amount of nitrogen stored in the living biomass. In the Baltic region, the societal contribution corresponds to an even larger enhancement over the natural terrestrial fixation (forests), which is around 1–2 kg N/year and ha.

Nitrogen is fixed industrially in ammonia synthesis. Ammonia is a basic chemical in industry and nitrogen is contained in products

Nutrients in the environment

The macronutrients (nitrogen (N), sulphur (S), phosphorus (P), calcium (Ca), potassium (K), sodium (Na), magnesium (Mg)) are elements needed in relatively large amounts in living organisms. The environmental status and availability of the macro-nutrients are very important for the composition, growth and vitality of ecosystems.

The conversion of macro-nutrients in nature is to a large extent connected with biological processes. These extensive processes heavily influence the state of the environment, for example, the acidity in soil, the chemical composition of surface waters and the radiative balance and chemistry of the atmosphere. In the evolution of the Earth, biological processes have been a major factor in the shaping of the cycles of the macronutrients, now determining the conditions for the biota in various ecosystems.

Here we shall discuss societal disturbances of the macro-nutrient cycles, not only because of the increased supply of nutrients to the ecosphere and the intensification of the cycles, but also because of disturbances of the ecosphere and redistribution of nutrients within it.

Fig 6.1 Natural streams have a good capacity for denitrification, which turns nitrate into nitrogen gas, and thus diminishes eutrophication.

such as nylon. However, the production of fertilizers for the agricultural sector produces the main demand for ammonia and is the major contributor to anthropogenic nitrogen fixation. To increase crop yields, biological nitrogen fixation is also enhanced by the choice of nitrogen-fixing plants (through symbiosis). Large amounts of nitrogen are stored in organogenic soils. Agricultural uses of these soils often rapidly activate and deplete this storage together with the organic material.

Fixed nitrogen is also emitted in combustion processes. This nitrogen has two sources. Some of it originates from the combustion air (thermal nitrogen and prompt nitrogen). Nitrogen is also present in the fuel (fuel nitrogen). The extraction of fixed nitrogen with fossil fuels amounts globally to approximately 60 Mtonnes per year, that is, the same order of magnitude as from chemical fertilizers; see Table 6.2. However, only a fraction of the fuel nitrogen reaches outside the combustion process because of pyro-denitrification of the fuel nitrogen in the combustion process (or because of any added nitrogen emission counter–measures.) The net effect on the balance of fixed nitrogen in the ecosphere depends on the fuel source. For fossil fuels there is a net contribution, while burning of biomass normally gives a net loss. Most of the fixed nitrogen is emitted as various nitrogen oxides, in summary written as NO_x.

Fixed nitrogen leaves the ecosphere through decomposition of nitrogen compounds to N_2, mainly through biological denitrification of nitrate into N_2; see Table 6.3. By sedimentation, part of the nitrogen is also withdrawn from chemical activity in the biosphere.

Combustion of nitrogen-containing biological materials may also contribute to losses of fixed nitrogen from the ecosphere. The burning of biomass in the tropics has been estimated to yield a loss of 5–52 Mtonnes organic N, which can correspond to a substantial fraction of the total biological nitrogen fixation in the area and may lead to a deficiency situation.

Table 6.1 Global nitrogen fixation by natural and anthropogenic processes

Natural processes	*(Mtonnes/yr)*	*Anthropogenic processes*	*(Mtonnes/yr)*
Biological fixation		Industrial production	
– land	90 – 130	of fertilizers	78
– ocean	40 – 200	Enhanced biological fixation	43
Lightning	3	Combustion	21

(Data from Galloway et al. [1995])

Combustion of nitrogen-rich biomass, such as forestry residues, in boilers with low emissions of fixed nitrogen (partly or wholly due to regulations) resulting in a net pyrodenitrification has been suggested as a way of compensating for the nitrogen excess due to air deposition in industrialized countries.

Where has all the extra nitrogen due to increased fixation gone? How much has accumulated in sediments or in other parts of the ecosphere and how much has been denitrified? These questions are still to a large extent unsolved [Galloway *et al.* 1995].

6.2 Sulphur supplied to the ecosphere

Sulphur in a reduced form can easily be oxidized and give rise to acidification. The main human-induced problems associated with the sulphur cycle are thus connected to emission to the atmosphere or exposition at the Earth's surface of not fully oxidized sulphur. Sulphur is extracted from the lithosphere in different ways:

- with minerals rich in sulphur, such as native sulphur or pyrite, that are extracted for their sulphur content;
- as sulphur impurities in fossil fuels;
- in metal-bearing sulphide minerals;
- as sulphates, mainly gypsum.

The first three forms contain sulphur in a reduced form, while in gypsum, a hydrated sulphate salt, the sulphur is already oxidized and neutralized. Table 6.4 gives an estimate of the amounts extracted from the lithosphere. Most sulphur extraction takes place with the extraction of fossil fuels, especially coal. Half of the sulphur in fossil fuels is emitted to the atmosphere. Less than half is caught in ashes or in desulphurization plants or is recovered for industrial use.

The mining of sulphidic metal ores gives rise to sulphur in mine tailings and dumps and brings sulphur into metallurgical processes. In the only Swedish smelter of sulphidic ores, the recovery of sulphur (as SO_2 and sulphuric acid) in the smelter is about 94 per cent and less than 2.5 per cent is emitted to air or water. On a world-wide scale the recovery is less. For example, the mean recovery factor of sulphur in global copper production is around 70 per cent.

The world-wide industrial use of sulphur is around 60 Mtonnes/year, that is, less than one-third of what is extracted from the lithosphere; see Figure 6.2. More than half of the sulphur is extracted from the by-flows associated with fossil fuels use and metals production. The major proportion is used for production of sulphuric acid which has a very diverse use in industry, although around 58 per cent goes into the extraction of phosphorus, another macronutrient used mainly in the production of fertilizers. For each kilogram of phosphorus, about two kilograms of sulphur are needed.

Anthropogenic emissions, mainly from the industrialized countries, make up three-quarters of total emissions. The transfer from the lithosphere is largely caused by the anthropogenic contribution, which is concentrated in the mid-latitude northern hemisphere. Society has increased the transfer from the lithosphere to

Table 6.2 Estimate of the extraction of nitrogen from the lithosphere with fossil fuels in 1989.

	Global use (1012 MJ/yr)	*Fixed fuel nitrogen (weight– %)*	*Specific heating value (MJ/kg)*	*Extracted nitrogen (Mtonnes/yr)*
Coal	94	1.5 (1–2)	27	52
Oil	130	0.3 (0.1–2.0)	42	9.3
Natural gas	72	negligible	49	–
Total	**296**			**61**

the atmosphere by about a factor of 10.

Natural redistribution of sulphur within the ecosphere, located mainly in the tropics, is principally caused by dimethyl sulphide (DMS) emissions from the ocean surface, while the anthropogenic part of the redistribution is connected with biomass burning. Natural redistribution is greater than the anthropogenic counterpart, albeit they take place mainly over the ocean and land respectively.

6.3 Phosphorus in agriculture

Phosphorus is extracted from the lithosphere, mainly in the form of various apatites (principally calcium phosphates). The main societal use of phosphorus, about 90 per cent, is as fertilizer in agriculture and the global use of fertilizers is estimated at 15 Mtonnes in 1985. Extraction has increased dramatically with the enhanced use of fertilizers (4.8 per cent/year since 1900). Phosphorus is also used as an additive in food and fodder. The second largest use is as a component in washing detergents. The use of phosphorus thus occurs to a very large extent within the food sector. In its other uses, most of the phosphorus is discharged in waste water.

In Sweden (as in many other countries), supplying phosphorus in fertilizers in recent years has exceeded its removal at harvest and therefore there has been an enrichment of the soil leading to a slowly growing increase of soluble phosphorus; see Figure 6.3.

6.4 Base cations

Base cations are extracted from deposits of sediment and evaporites in the lithosphere. They are used as fertilizers and pH-regulators in agriculture, as base chemicals in industry and in the manufacture of cement, which has led to their accumulation within infrastructure and buildings.

Base cations are brought with the extracted fossil fuels. Burning fossil fuels gives alkaline bottom and fly ashes. Earlier the fly ash partly compensated for the acidic components in the exhaust gases. But the fly ash is easily caught in filters and was one of the first emissions to be decreased, thus increasing the acidification potential of the untreated parts of the emissions. This tendency is illustrated in Figure 6.4.

6.5 Increased leakage and redistribution of macronutrients

Besides the increased input in the macronutrient cycles, there is an increased leakage and redistribution of the nutrients available in the ecosphere. The substitution of highly manipulated cultural ecosystems for natural ecosystems in agriculture, and also to some extent in forestry, and intensive animal husbandry have led to large increases in the leakage of nutrients, especially nitrogen, to air and water and further to various ecosystems. Their leakage varies with the specific system and the applied practice, but is larger than in the natural system they have replaced. While natural systems have been forced during evolution to develop and rely on fairly closed nutrients cycles, agricultural ecosystems are driven towards other goals and also have the possibility of being compensated for their losses of nutrients. For nitrogen, the major leakages are ammonia to air from stables and manure and nitrate to water from agricultural soils. Ammonia (NH_3) emitted to air is the source of approximately half of the atmospheric deposition of nitrogen compounds in Europe.

Within societal systems for growing, handling and using organic materials, there are large redistributions of nutrients bound to organic materials taking place at various levels and scales. In agriculture, specialization leads to fodder redistribution and concentration of nutrients in animal-rich farms and regions. In soils with no recycling of harvested products, nutrient deficiency will quickly develop if there is no external supply. Trade in food and fodder takes place on a global scale, depending on, for example, soil abundancy and conditions for growing different crops and economic circumstances.

The food system also implies inflows of nutrients from the countryside to villages and towns where they end up in waste and sewage. Figure 6.3, depicting phosphorus flows in Sweden, illustrates the importance of these flows. Modern wastewater treatment systems do not recover nutrients in sewage sludge to any extent except for phosphorus. Also, much of the sludge is not recycled back to agricultural soil.

Forestry and the transportation of forestry products contribute. For example, the harvest contributes to an important withdrawal of base cations which, for instance, may end up in ashes when the material is burnt to get rid of waste or for energy purposes. On the other hand, modern forestry practices have more or less eliminated forest fires and the associated losses and redistributions of nutrients.

Table 6.3 Processes giving rise to losses of fixed nitrogen from the ecosphere.

Natural processes	*Societal processes*
Decomposition	Decomposition
• Biological denitrification	• Biological denitrification
• Pyrodenitrification	• Pyrodenitrification
• Photolysis of N_2O	• Catalytic processes
Outflow to the lithosphere	
• Final sedimentation	

Table 6.4 Global anthropogenic extraction of reduced sulphur from the lithosphere.

Extraction of	*Minerals mined (Mtonnes/yr)*	*S content (% S by weight)*	*S mined (Mtonnes S/yr)*
Sulphur			14
Pyrite (FeS2)		10	
Fossil fuels			
– hard coal	3340	1.8	60
– lignite	1280	1.3	17
– oil	3051	1.2	37
– natural gas		15	
– tar sand		1	
Metal sulphides			
– to mineral processing		12	
– to mining waste			> 24
Total			**> 190**

6.6 Environmental problems

Many environmental problems are the consequences of extensive human disruptions of bio-geo-chemical cycles and stocks and flows of macronutrients which consequently disturb the basic chemical and physical conditions for living organisms. The effects vary in scale from local effects to global problems.

i) Enhanced growth

Most ecosystems are deficient in nitrogen or phosphorus, that is, they react by enhanced growth to additional such nutrients. Extensive addition of nutrients through deposition or with the influx of water may then lead to eutro-phication of the ecosystems. In lakes, water courses and some coastal regions of the sea, phosphorus is the principal deficient nutrient while nitrogen is limited in most terrestrial ecosystems. One consequence of eutrophication is changes in the composition of the ecosystem. The changes can threaten the existence of species and cause oxygen deficiency in aquatic systems which, in turn, may lead to total extinction of life over large areas, for example, in coastal waters.

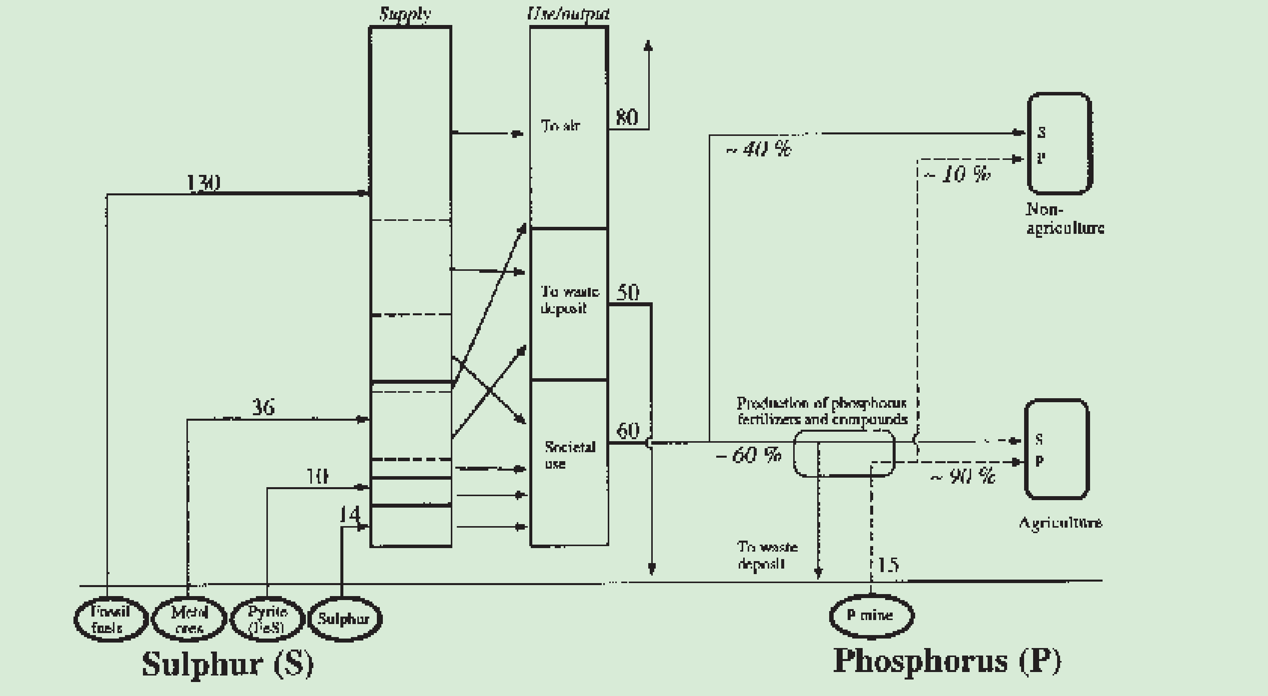


Figure 6.2 Global anthropogenic flows of sulphur (Mtonnes S/year). Data from Karlsson et al [1994].

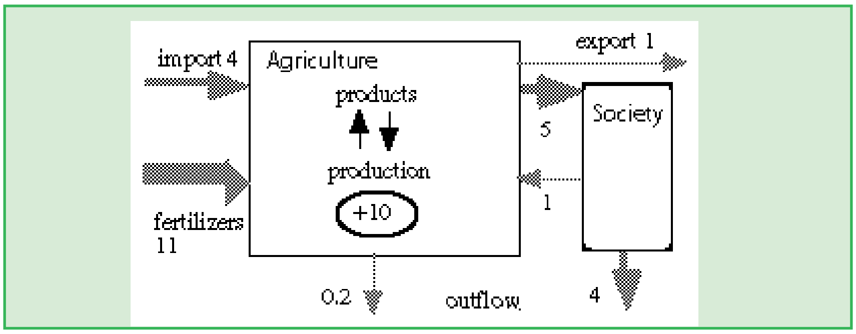


Figure 6.3 The flow of phosphorus in the socio-agricultural system in Sweden in 1990 (kg/ha–year). The food industry is included in 'Society'. (Data from Granstedt & Westberg [1992].)

ii) Acidification

Chemical processes within the nitrogen and sulphur cycles and the uptake and mineralization of all the macronutrients affect the hydrogen-ion balance and thus the acidity of the water where they take place, for example, the water in soil or surface water. The processes involve changes or transfer of electrical charges which in the end are balanced by hydrogen ions.

For instance, uptake by a plant of a calcium ion, Ca^{2+}, from soil solution transfers two hydrogen ions, H^{+} to the soil solution. The oxidation of ammonium, NH$_4^+$, to nitrate, NO$_3^-$, also leads to two more hydrogen ions in the soil solution.

However, within closed cycles of the macronutrients, different processes compensate for each other. But any disruption jeopardizes the balance. These disruptions can be caused by, for example, excess addition of sulphur and nitrogen through deposition, leading to leakage of nutrients or withdrawal of base cations through extensive harvesting of the biomass. Natural processes also contribute by the leakage of nutrients or acidic carbonous compounds. However, weathering of soil, which maintains a buffering capacity with base cations, compensates to a certain extent. But there is natural slow long-term acidification of soil in coniferous forests at our latitudes (podsolization).

The deposition of sulphur is the main contributor to the man-made acidification of soil and water. But the oxidation of reduced sulphur in various sulphides exposed to oxygen in deposited waste from mining of metal-rich sulphide minerals may also give rise to increased acidity and consequential increased mobility and leaching of metals from the waste.

iii) Other environmental impacts

Atmospheric emissions of nitrogen and sulphur species also have a profound influence on the chemical and physical properties of the atmosphere. Emitted sulphur dioxide is converted to sulphuric acid and forms aerosols, which disturb the radiation balance resulting in a net cooling of the Earth's surface. In various processes, some of the fixed nitrogen can be converted into dinitrogen oxide (N$_2$O), which is a greenhouse gas and influences the stratospheric ozone layer. Other nitrogen oxides take part in a number of chemical reactions in the atmosphere and may enhance the concentrations of important oxidants, such as ozone (O$_3$) and the decidedly noxious smog component peroxyacetyl nitrate (PAN).

Unhealthy concentrations of both sulphur and nitrogen oxides are reached regularly in cities, and a corresponding effect happens with nitrates in drinking water, primarily in agricultural areas with intensive cultivation. Plants can also be damaged by too-high concentrations of nitrogen compounds in the air.

6.7 Nutrient resources

The long-term availability of macronutrients is crucial to human society because of their importance in food production. The fixation of nitrogen is an energy-intensive process both in biological and industrial processes. However, nitrogen itself is available from the air in unlimited amounts.

Sodium is presently mostly extracted in salt mines but is also available in unlimited amounts from the sea. Other macronutrients are taken from relatively abundant lithospheric deposits. Only phosphorus is considered to be scarce. Its content in the crust,

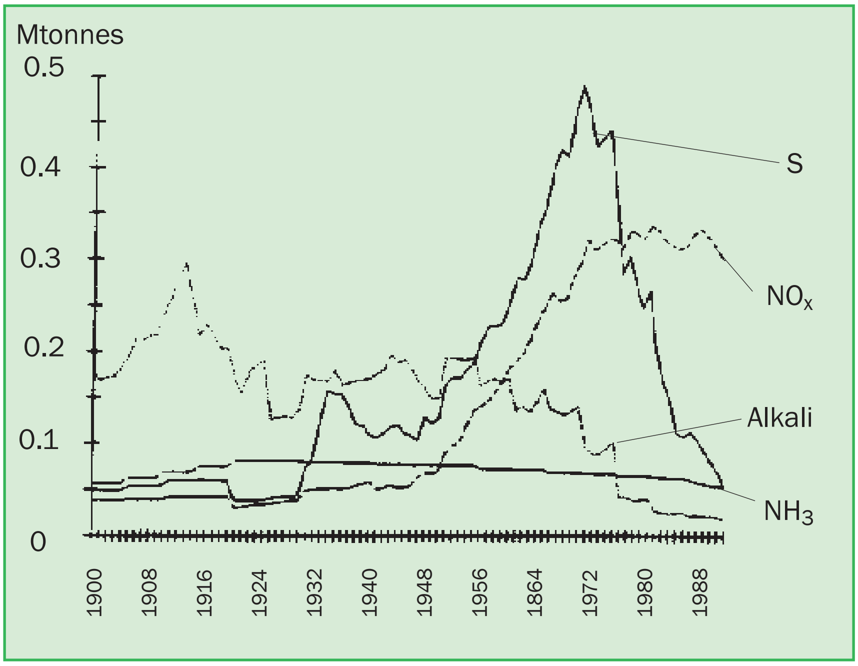


Figure 6.4. The emissions of alkaline and acidic components in Sweden (Kindbom et al. [1993]).

around 0.1 per cent, is quite low, and much soil around the world is deficient in phosphorus.

6.8 Future prospects

We have to decrease the inflow and redistribution of macro- nutrients. Their connection with human intentions vary. Some flows are by-flows, as in fossil-fuel use. Other are highly intentional, as in agriculture fertilization. Some are leakages from natural and cultural ecosystems depending on management practices.

Elimination of fossil fuels as a means of halting the increasing greenhouse effect will solve part of the problem. Withdrawal of fossil coal and oil will substantially eliminate disturbances of the sulphur cycle. However, a switch to natural gas, which contains only small amounts of sulphur, is also possible. Increased metal recycling and less accumulation in the technosphere will lead to less reliance on virgin metal resources and thus diminish the by-flows. Any remaining problems with lithospheric excavations may possibly be kept low with technical control measures fulfilling strong emission standards.

Agriculture and forestry and the connected industry, energy and consumer sectors have to close the cycles of nutrients by reducing leakage and redistribution on various scales within the production system. The one-way flow from production to consumption, and further to the environment with waste streams, needs to be halted and nutrient flows redirected back to the production system. This will lead to a reduced load on the environment and less need for input of new nutrients to compensate for the losses. However, human-made and human-managed ecosystems will probably never be as closed as the natural ones. An important question is therefore which losses and disturbances in the nutrient cycles we may have to accept.

Society's need for sulphur is heavily dependent on the development of phosphorus extraction for fertilizer production, which so far has been increasing globally. Some of this sulphur is also included in the fertilizers which may compensate for the repeated withdrawal of sulphur with the harvests. With unchanged agricultural practices and a reduced atmospheric deposition of sulphur, agricultural soil will soon develop a sulphur deficiency.

Figure 6.2 Use of phosphate-containing washing detergents for laundry is an important contributor to phosphorus emissions to waste water. In many cases the poly-phosphates in the detergents have been substituted by non-phosphorus-containing chemicals.

7.

THE VALUABLE METALS

7.1 Metals in nature and society

Pure metals are characterized by being opaque, tough, ductile and malleable and in possessing high thermal and electrical conductivities. Approximately half of the chemical elements possess some metallic properties but a true metal has two or more of the special metallic properties.

Some of the metallic elements are essential to life but most of them are non-essential. The essential metals do not constitute major building-blocks in life. Instead, they are trace elements and fulfil quite specialized functions, bound in enzymes and other types of molecules. The turnover of metals in plants and animals is thus quite small.

As opposed to life processes, in which metals exist as ions, society uses metals mainly in their pure form and for their metallic properties. Today, approximately 30 metallic elements are made commonly available in society through mining and processing of their ores. Many metallic elements are used in their pure forms, however, because of their unique properties. Chemical mixtures (alloys) of two or more metals, or metals and non-metals, often have superior properties of corrosion resistance, durability or strength.

Iron totally dominates societal use of metals; see Table 7.1. As already concluded in Chapter 3, compared to other materials flows in society, the flows of metals, except for iron, are relatively small. But metals are technically and economically very important to industrialized society and this is reflected in their relatively high prices. Many other metals are closely linked to the use of iron as *ferro-alloy metals*. Partly because of their relatively low weight, society uses an increasing amount of the abundant light metals, especially aluminium, but also titanium and magnesium.

Society still also uses a lot of the traditional *non-ferrous metals* or *base metals*, for example, copper, lead, zinc, tin and mercury.

The *precious metals* of antiquity, gold and silver, were called noble metals. Today the so-called platinum group elements are also

Table 7.1 Metals in nature and global extraction of metals

Metal	*Type*	*Conc. in soils [mg/kg]*	*Global mining [ktonnes/year]*	*In extracted fossil fuels [ktonnes/year]*	*Mining + fossil fuels/ cont. weathering*[a)]
Aluminum, Al	Abundant light	72 000	18 000	34 000	0.05
Iron, Fe	Abundant	26 000	540 000	34 000	1.5
Magnesium, Mg	Abundant light	9 000	3 100	690	0.03
Titanium, Ti	Abundant light	2 900	2 500	1 700	0.10
Manganese, Mn	Ferro-alloy	550	8 600	170	1.1
Vanadin, V	Ferro-alloy	80	32	350	0.32
Zinc, Zn	Base-metal	60	7 300	260	8.3
Chromium, Cr	Ferro-alloy	54	3 800	34	4.6
Copper, Cu	Base-metal	25	9 000	55	24.0
Nickel, Ni	Ferro-alloy	19	880	570	4.83
Lead, Pb	Base-metal	19	3300	85	11.67
Cadmium, Cd	Base-metal	0.35	20	3.4	4.42
Mercury, Hg	Base-metal	0.09	5.2	10	10.86

[a)] Mobilization in continental weathering is calculated using average concentration in soils (column 1) and suspended sediment flux of $1.5 \cdot 10^{16}$ grams per year in rivers [Nriagu 1990].

Source: Azar *et al.* 1996

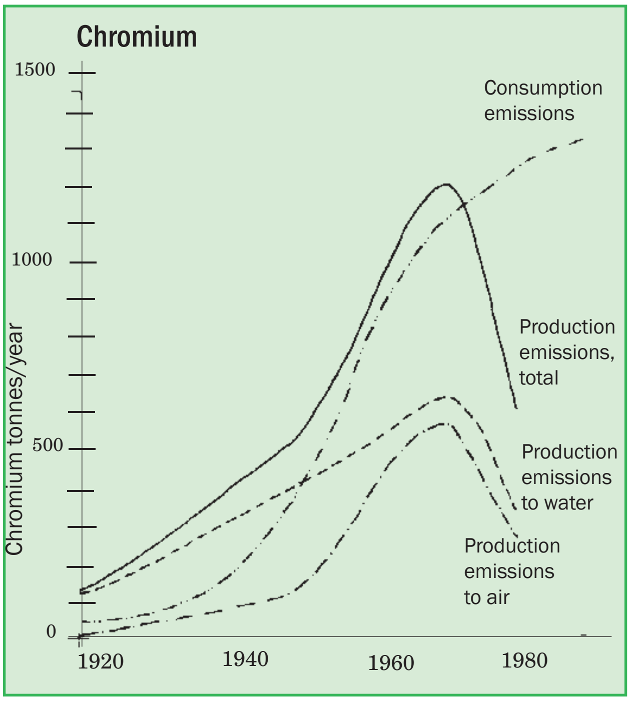


Figure 7.1 a) Emission of chromium from the production and the consumption of goods containing chromium, inclusive of emissions from incineration and leakage from waste deposits. Sweden 1920-1980.

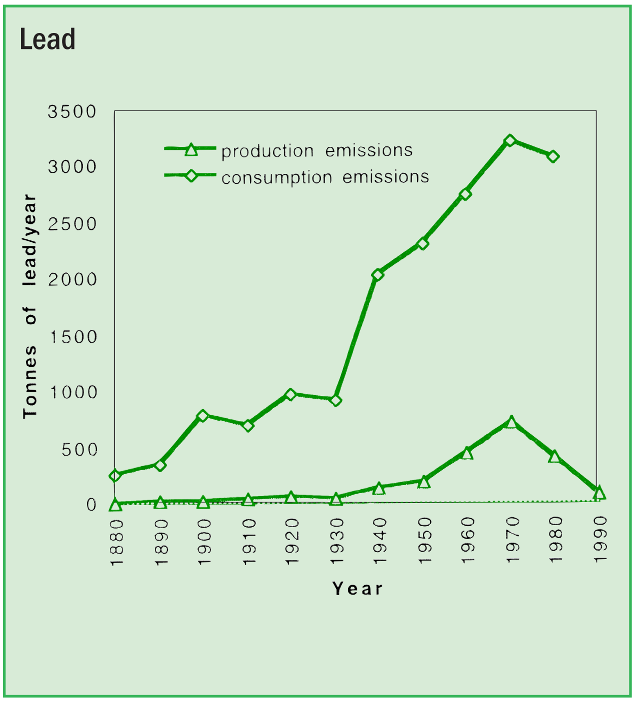


Figure 7.1 b) Emission of lead from the production and the consumption of goods containing lead.

called precious or noble metals because they too exhibit non-reactive properties.

Finally, there is a group of metals, the *special metals*, that do not fit into the categories mentioned above. These metals have unusual properties that make them important in industry. Tantalum, for example, is widely used in electronics because of its special properties.

7.2 The ecological rucksacks of metals

Many metals are scarce but valuable and are therefore extracted from ore of a low grade. Despite the relatively low volume of extracted useful metals, some metals contribute extensively to the ecological rucksack. Iron, because of the large volume used in society, and copper, because of its low-grade ores, give rise to huge amounts of discarded useless materials in mining and concentrating operations and also in subsequent metallurgical processes.

The extraction of five grams of gold (about the amount in a wedding ring) needs the excavation of around one cubic meter of lithospheric materials.

The rucksacks consist mainly of large dumps and translocations of materials at the mine and may give rise to mainly local effects. They are therefore probably of minor importance from the perspective of sustainable development. If mining is done in agricultural areas, it can imply serious problems for these areas. Leakage of metals from mines and overburden can also imply long-term effects on the local environment.

7.3 Emissions of metals

Emissions of metals to the environment can occur all along the chain from the cradle to the grave. Emissions from the production system have historically increased with increased production during industrialization. Fortunately, the environmental restrictions introduced in later years have drastically reduced these point emissions to water and air from the production system. Instead, today, major emissions of metals to the environment in modern industrial systems tend to emanate from the consumption phase of the goods and not from their production, which can be illustrated by the estimated emissions from the historical turnover of chromium and lead in Sweden (Figure 7.1) [Bergbäck 1992]. This is also true for the copper flow (see box).

There is a huge range in consumption losses between various types of use, as indicated, for example, by the crude estimate given in Table 7.2. We have uses of metals that are intrinsically dissipative in their character. In chemical uses especially, metals are spread intentionally either already as products or in their uses as in, for example, paints and biocides. However, there are also intentional losses involved in metal uses, such as the lead used in ammunition. Losses from wear and tear or corrosion of products also vary considerably. For example, use of copper that give rise to emissions include, copper used outdoors and exposed to weathering as in roofing and facing materials, copper exposed to liquid flows as in tap-water systems and heat exchangers and copper in braking pads. The dissipation of the metals are concentrated to the places where the metals are used, that is mainly in towns and villages and where our industry and infrastructure are located. Locally the emissions to soil and water can be very high.

However, for metals, the major system losses tend to emanate, not from direct emission to the ecosphere, but from *lack of recycling*. System losses mean metals in the technosphere that are taken out of use but are then are not recycled such as flows to deposits through waste-handling or materials simply left behind when no longer in service. The copper flow illustrates this (see box). Large flows of copper recovered by the waste-handling system are not recycled, but are ultimately deposited in land-fills. A lot of copper in cables laid down in the ground, for example, is not recovered when the cables are taken out of service.

When recovered metal is of suitable quality, today's production technology often makes it possible to keep a very closed metal system, which can be exemplified by the lead system (See box). This is also underscored by the fact that secondary production of metals often has much less specific loss than the corresponding primary production.

7.4 Scarce and abundant metals

Potentially extractable metal ore deposits are suffering from various degrees of scarcity. Extraction is coupled to extensive manipulation and the intensive and often dissipative use of metals has led to severe contamination of the environment and threats to human health.

One important observation that can be made from Table 7.1 is that certain metals that are scarce in nature are not scarce in society. The relatively large use of many of the scarce heavy metals compared to natural turnover has an important implication: societal use of these metals has a large potential for producing substantially increased concentrations of them in the ecosphere. Limited assimilative capacity in natural systems sets restrictions on the uncontrolled emissions of these metals. Contamination by heavy metals has also been a serious environmental problem so far during industrialization. The light metals are in a better position in that their societal use is small compared to natural turnover.

Metals can be separated in two main groups, abundant and scarce, on the basis of their abundance in the Earth's crust; see Table 7.1. The *abundant* metals are those that individually make up at least or almost 0.1 per cent by weight of the Earth's crust. There are very few such metals: iron and the light metals aluminium, magnesium and titanium and then, at almost 0.1 per cent, manganese. All other metals occur in much lower concentrations, near to 0.01 per cent and less, and are categorized as geochemically *scarce* metals.

The abundant metals are available in increasing amounts in lower grade down to the common rock, from which they can be mined directly. It is argued therefore, that society will never experience a sudden scarcity of these.

All metals are mined from ores rich in specific separate minerals containing metals. The ores are ground and the metal-bearing minerals are separated and concentrated before metallurgical treatment in which the metals are extracted from the minerals. In the Earth's crust, however, the scarce metals are very seldom concentrated in separate minerals, but most often are found, in small concentrations, stochasti-cally distributed as substitutes for other elements in the minerals of ordinary rock. It is not possible to grind these minerals to separate specific atoms or molecules. Instead the metallurgical process has to treat all of the ordinary rock, which make the metal practically unavailable. This has been called the 'mineralogical barrier'. It has been estimated that not more than one in 10^4 to 10^5 of the total amount of each metal is located in a separate mineral. This can give a rough estimate of the ultimately recoverable amounts [Skinner 1987]. Table 7.3 shows some estimates using this measure together with today's reserves.

7. 5 Access to metals in the long term future

The limited amounts of metal resources are of both intergenera-tional and intragenerational distributional concern. Intergenera-tional justice must be met by low *system losses* in quantity and quality, not necessarily less extraction. Scarcity of resources often leads to the claim for restrictions on extraction. However, the extraction of metal resources is not a loss, but an investment, at least in the short run, and an associated cost. Put in other words: the extraction of limited metal resources is not in itself a waste of these scarce resources, but implies lower future costs due to the increased availability of the resources. The real losses of resources are those losses from the technosphere, which imply future costs for replacements. From a *resource perspective*, it is thus better to have copper in a cable and maybe also in a waste dump than to have copper in an ore.

Intragenerational distribution puts restrictions on the accumulated *per capita stock* of resources

Table 7.2. Estimated emission factors from various consumptions of different metals. (defined as losses to the environment during a 10 year period)

Use / Metal	Ag	As	Cd	Cr	Cu	Hg	Pb	Zn
Metallic use	0.001	0.001	0.001	0.001	0.005	0.05	0.005	0.001
Plating. Coating	0.02	0	0.15	0.02	0	0.05	0	0.02
Paint, Pigments	0.5	0.5	0.5	0.5	1.0	0.8	0.5	0.5
El. tubes, Batteries	0.01	0.01	0.02	na	na	0.2	0.01	0.01
Other electric equipment	0.01	na	na	na	0.1	na	na	na
Chem. uses in final prod.	0.4	0.05	0.15	0.05	0.05	na	0.75	0.15
Chem. uses not in final prod.	1	na	1	1	1	1	1	1
Agricultural biocides	na	0.5	na	na	0.05	0.8	0.05	0.05
Non-agric. biocides	na	0.8	na	1	1	0.9	0.1	0.1
Medical, Dental	0.5	0.8	na	0.8	na	0.2	na	0.8
Miscellaneous	0.15	0.15	0.15	0.15	0.15	0.5	0.15	0.15

between various groups of people. The per capita accumulated intake of some metals during industrialization has been large compared to future possibilities; see Table 7.3. Thus, there are restrictions on the global spread of industrialization with the same intensity of use of metals as historically in the already industrialized countries. In a situation where there is restricted availability of primary metals, precisely who should have access to the technospheric pools of the historically accumulated metals may become a significant future distributional question. So far, the pools are overwhelmingly in the already developed countries and the growth of the pools of various metals in the technosphere is still going on in industrialized societies.

Metal resources and uses are interconnected. A metal ore often contains more than one valuable metal and many minor metals are today mined only as by-flows to the extraction of other major metals. For example, cadmium is mined together with zinc, and a decrease in cadmium use may not lead to a decrease in cadmium mining as long as the economics of zinc dominate. However, zinc is today mainly used to dematerialize another metal use, the use of iron, by protecting iron from corrosion and losses. These interconnections put restrictions on future metal use.

7.6 Strategies for sustainable metal use

In Chapter 4 we discussed different possibilities for achieving sustainable materials flows. That discussion of course also applies to the use of metals. There are two main strategies:

1) to reduce the impact of metals on nature and
2) to save important metals for the future.

It is possible to reduce losses of metals by *dematerialization*, for example, by achieving more closed cycles within the techno-sphere. It is possible to substitute hazardous metals for less harmful materials as well as to concentrate the use of special scarce elements in important uses, both cases of *transmaterialization*.

But how far should these strategies be taken? When are emissions to the ecosphere, the system losses discussed in the last paragraph, acceptable? When should we recycle and when should we substitute? Should certain metals be avoided or should certain uses be transmaterialized to other materials or both? Figure 7.4 illustrates these questions schematically. In Sweden, according to a Government Bill passed in Parliament in 1991, the use of mercury, cadmium and lead is to be restricted and, in the long run, phased out completely from the technosphere. But is this situation of these metals not being used at all the only long-term option for their sustainable use? Could we instead have metals in certain uses in a sufficiently closed system within the technosphere? It seems reasonable that any phase-out should depend on the toxicity of the metal. But, for example, should very toxic elements be substituted for whatever the use and is it reasonable to have a non-restricted use of non-toxic metals whatever the character of the use?

In the short term, to avoid direct emissions, a metals policy focusing on consumption with large inherent dissipative losses of metals, which are environmentally harmful or have large flows compared to natural turnover, can thus be efficient to decrease hazardous emissions. The efficiency of various counteractions will depend very much on the function of the dissipating metal and the rôle of consumption in each specific case. The metal may not be the main flow nor even incorporated in the final product. Lead in petrol is a good example. There may be competitive technological options available, fulfilling the services required, as with various materials options for roofing and piping. Generally, development or use of technological options for substitution at various levels should be more efficient than dematerialization of the main flow or simply avoiding or lowering the use.

If we want to close the loops

The flow of copper

It is interesting to study copper because the societal flow of copper is very large compared to the natural flow. This means that there is a great risk of an increased concentration of copper in the environment.

In summary the scheme shows that: accumulation > flows to deposits > intentional dissipation (part of function) in consumption > unintentional dissipation in consumption ≈ emissions from point sources in production (based on Nilarp 1994; See also Norrthon 1996).

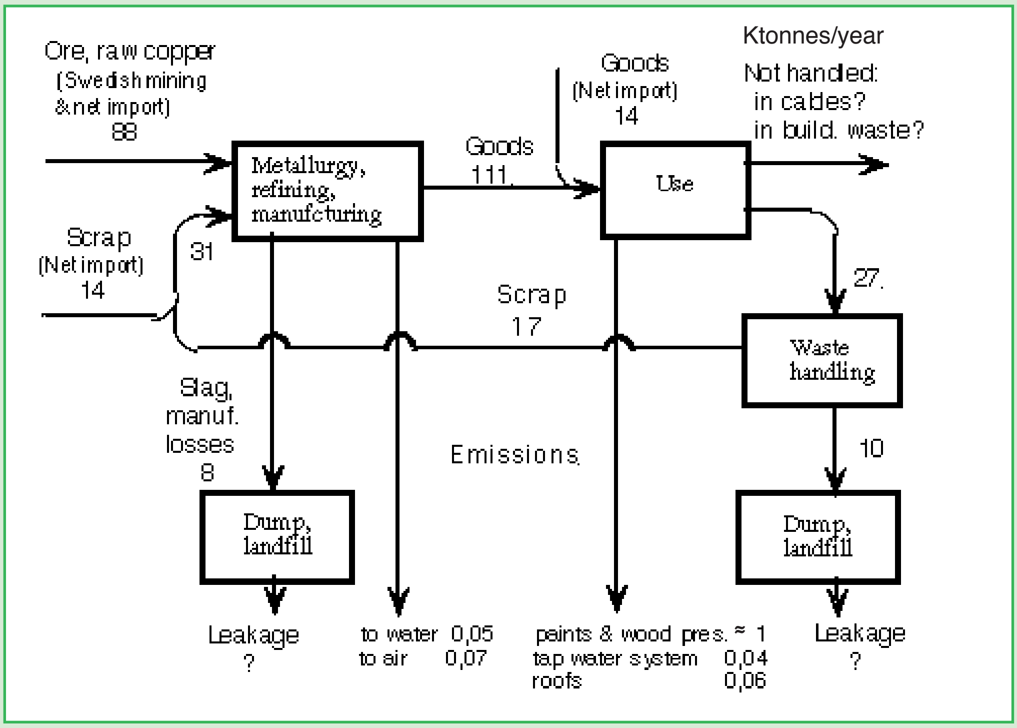


Figure 7.2 The flow of copper in the Swedish technosphere.

We can draw the following conclusions about the use of copper:

- The intake of copper into the technosphere exceeds the outflow from production and consumption systems. This means that there is still a continuous accumulation of copper in society in, for example, buildings, infrastructure and consumer goods. There is also a large accumulation in various dumps, in tailings at mines (outside the figure) and in deposits of production and consumption waste.
- The diffuse and unintentional leakage from various products such as copper roofs and the tap-water system, exposed to wear and tear or corrosion, is of the same order of magnitude as emissions from industry.
- The flow due to the intentionally dissipative use of copper, such as in the use of copper-containing impregnating agents, is even greater than the unintentional flow from copper roofs and the tap-water system, etc. Consumption emissions are thus larger than production emissions.
- The major amount of copper in used products dealt with by the waste-handling system is recycled. However, a considerable proportion is deposited in dumps and landfills.
- It is difficult to estimate the amount of copper which is not dealt with by the waste-handling system but is left behind when no longer in use as, for example, copper in electrical cables in the ground. A recent estimate for this category is two to six kilotonnes a year (Norrthon 1996). These cables can imply a large future leakage. Companies which have been using these cables have very little information about these flows.
- Copper which is not recovered and recycled, but instead goes to deposits or is left behind, constitutes the largest system loss in the turnover of copper.

Fig 7.3 Lead in car batteries constitutes a major part of the flow of lead in society. It is comparatively easily subjected to efficient recycling strategies.

within the technosphere, it is important to know how closed the system can be and which parameters are the dominating factors. For instance, in the lead-acid battery system (See box), the production system has the potential for fairly low losses (compared to, for example, natural flows) and the recovery of the batteries after use is a very important factor. The answer is crucial because lead is considered to be one of the metals that most threatens human health; it is non-essential to biota and the anthropogenic mobilization of lead from the lithosphere is much larger than the corresponding natural flow. We can argue that if it is possible to have large-scale use compatible with long-term environmental and health requirements, we may not have to choose a complete phase-out policy, but instead can regulate specific uses. The policy of directing effort towards the use of the metal rather than the metal itself may serve as a pattern for the sustainable use of other metals as well.

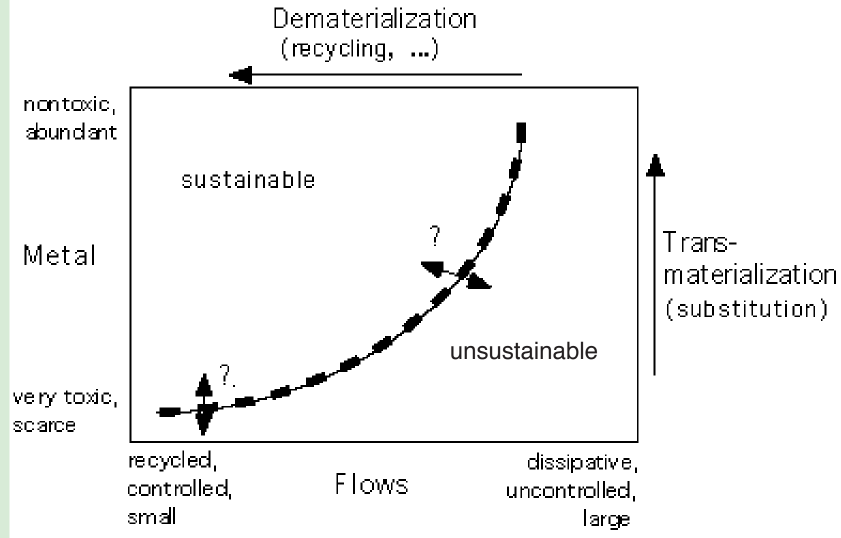


Figure 7.4 The more toxic or scarce a metal is, the more recycling and controlled flows are necessary. However, there is still ambiguity about exacly what is sustainable. To achieve a more sustainable metal use, there may be a choice between dematerialization (that is closing the technospheric loops) and transmaterialization (substitution to more abundant or less harmful metals or possibly other materials).

7.7 Long term metal use requires recycling

The potential for recycling metals is very high. Metal atoms are not degraded during use and recycling. They can in principle be recirculated for ever. Instead metals may be successively degraded by impurities influencing their quality, which severely restricts their future use. In using metals we mix different metals with each other, either intentionally as in alloys or in, for example, recycling processes due to incomplete separation. Shredding car scrap tends to contaminate iron with copper which, even in small concentrations, reduces the applicability of recycled iron. (This degradation of the technospheric stock of materials has been called 'techno-toxicity', [Norrthon 1996].) In order to

The flow of lead – and recycling batteries

For toxic metals, recycling is evidently very important. We shall look more closely at one case; the flow of lead through the Swedish system. The lead budget in Sweden in 1989, shown below, amounted to about 35,000 tonnes in total. This corresponds to about 4 kg/capita which is close to the European average. Of this some 20,000 tonnes, or 60 per cent, were recycled; mainly car batteries. The rest, some 15,000 tonnes, was supplied from mines and lost from the system. Outlets to air and water, registered by local authorities, comprised about 500 tonnes. Lead deposits in landfills, not registered were however substantially more, about 3,000 tonnes.

This means that some 11,500 tonnes of lead were accumulated in the technosphere each year. An average figure for the last 100 years is 21,000 tonnes. Thus, in total, some 2 million tonnes of lead have been taken into the Swedish technosphere during the last 100 years. This amount gives rise to a calculated emission of some 1,750 tonnes per year. It is again far more than the 500 tonnes registered by local authorities.

We can get a rough understanding of the size of these flows by comparing them to various measures of natural turnover. Weathering amounts to some 500 tonnes of lead per year, while leaching from Swedish agricultural soil has been estimated at 23 tonnes/year.

A special study was conducted on the losses of lead in the production and recycling of car batteries. The total turnover of lead in this recycling system amounts to 20,000 tonnes per year. The loss of lead from the system depends on the recovery rate as shown in the figure. With recycling rates up to 99.97 per cent, the predominant lead losses occur in the use and recovery of batteries. If the recycling rate is greater with lead going into by-products, losses to air and water, etc. will dominate with some 10 tonnes per year. This unavoidable outflow, about 0.5 promille, is several orders of magnitude less than the loss from the lead system as a whole.

However there are some further restrictions. If recycled lead is to be refined and reused in battery manufacturing without any significant change in overall battery performance, it must meet certain quality criteria. Today contamination of lead with bismuth, silver and some copper is considered to be the main issue, but most probably this can be overcome easily.

The recovery rates discussed here, 99 per cent or more, will give us a residence time of lead in the system far beyond our present planning horizons. These are 400 years for 99 per cent and 9000 years for 99.9 per cent recovery. This raises the question of how to handle the lead when it is taken out of circulation, for example, because of new technologies. Similar questions are already being dealt with in respect of radioactive waste and plutonium.

(Sources: Tiberg, 1991, Karlsson et al., 1996, Bergbäck 1992 and Andersson et al., 1988).

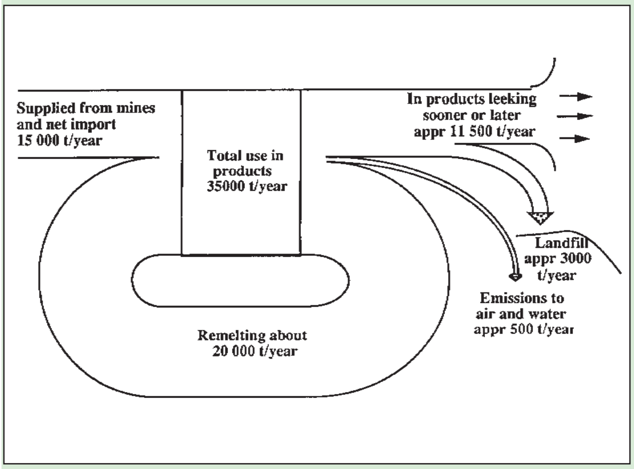


Figure 7.5 The losses of lead from the modelled lead-acid battery system as a function of the fraction not recovered for recycling. For no recycling at all and high recycling rates, corresponding to the left and right end, the losses illustrate the attributes of the primary and secondary industry, respectively. The secondary industry has much lower specific losses (losses per turnover) than the primary industry.

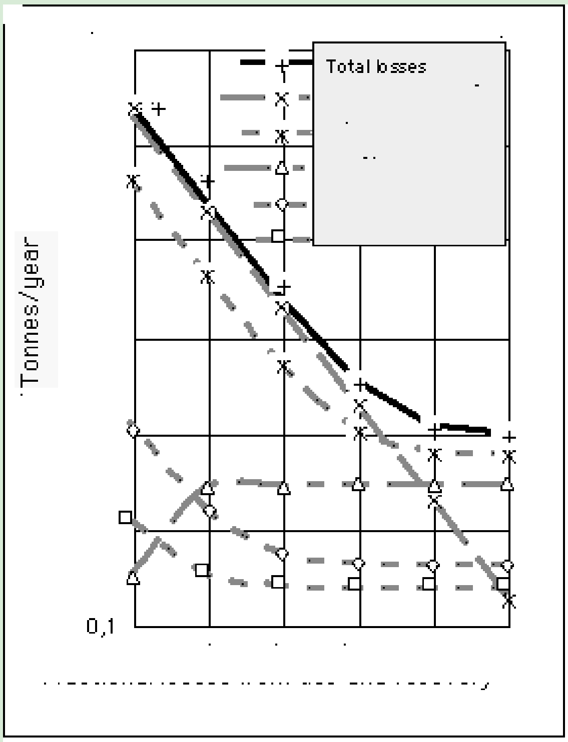


Table 7.3. Present per capita accumulated use of metals compared to various measures on future available amounts of metals per capita.

Metal metal use per capita	Accumulated per capita [Kg] (1 Gcap[a])	Reserves per capita [Kg] (10 Gcap[b])	Resources[c] per capita [Kg] (10 Gcap[b])	Resources (max[d]) [Kg] (10 Gcap[b])
Abundant metals				
Al	488	430	800	very large
Fe	18 400	6 600	23 000	very large
Scarce metals				
Zn	280	15	440	1540
Cr	95	42	340	1510
Cu	344	32	230	960
Ni	28	5	13	1160
Pb	180	7	140	250
Cd	0.71	0.05	0.6	2.1
Hg	0.9	0.01	0.06	1.5

[a] One billion people are assumed to have used the major fraction of extracted metals so far.
[b] A global population of 10 billion people is assumed.
[c] Crowson [1992].
[d] Maximum resources have been estimated as $10^{-5} – 10^{-4}$ of all materials in the Earth's crust to a depth of 4.6 km [Skinner 1987]. Here the maximum estimate is used.

avoid mixing (degradation) it is important to have various metals as well as various alloys separated from each other, for example, through a 'design for recycling'. But it is also necessary to develop recovery and recycling processes. To make it possible to achieve high-quality recycled metals, it may be necessary to decrease the number of various alloys.

In the *long term*, the pool of metals so far accumulated in society and available in resources is large compared to nature and constitutes a future threat. The accumulation of most metals is also still going on. This pool tends to leave the technosphere sooner or later. The long-term question is what are the acceptable final storage places for this pool and how can the metals get there. Today, losses are predominantly to waste deposits. With more closed cycles the losses are smaller but a larger proportion of these losses may be less controlled. With closed cycles the question is also partly transferred to future generations.

The scarcity and interconnection of metal resources may restrict the future use of metals to specific high-value applications and influence the choice of technology and the expansion rate of various applications. This restriction can have important implications for strategic choices among possible future key technologies within, for example, energy conversion and storage. Policies involving reliance on large-scale introduction of technologies, with inherent intensive utilization of scarce metals as the means of solving specific environmental problems, can thus be questioned. For instance, this may apply to certain battery-powered electric cars as a substitute for vehicles using internal combustion engines. Metal resources are also of great importance for the possible expansion of various types of thin-film solar cells.

8.

REFERENCES

General references

Bergbäck, B., 1992. *Industrial metabolism - the Emerging Landscape of Heavy Metal Imission in Sweden*. PhD thesis, Linköping University, Sweden.

Holmberg J, 1995. *Socio-Ecological principles and indicators for sustainability*, PhD thesis, Institute of Physical Resource Theory, Chalmers University of Technology and Göteborg University.

Hunhammar, S., 1994. Residues on the move, AFR-report 43, Swedish Environmental Protection Agency, Stockholm, Sweden.

IPCC, 1995. Climate Change 1994. *Radiative forcing of climate change*, Houghton, J.T., Meira Filho, L.G., Bruce, J., Hoesung Lee, Callander, B.A., Haites, E., Harris, N., and Maskell, K., (eds), Cambridge University Press, Cambridge, UK.

Karlsson, S., Azar, C., Eriksson, K.-E., Holmberg, J., Lindgren, K. & Wirsenius, S., 1994. *Materials Flows. On the Metabolism of the Industrial Society in a Sustainability Perspective,* AFR-report 38, Swedish Waste Research Council, Stockholm.

Karlsson, S., Berndes, G. and Wirsenius, S., 1996. *Global biomass requirement. Sustainable use of lead* AFR-Report 121. Swedish Environmental Protection Agency, Stockholm.

Månsson, B., 1993. *Miljö för bärkraftighet*, Liber-Hermods, Malmö. (In Swedish)

Robèrt, K.-H., 1994. *Den naturliga utmaningen*. Falun, Sweden, Ekerlids Förlag. (In Swedish.)

Schmidt-Bleek, F., 1994. *Wieviel Umwelt brauch der Mensch?* Birkhäuser, Berlin.

Schmidt-Bleek, F. & Tischner, U., 1995. *Produktenentwicklung, Nutzen gestalten – Natur schonen*. WIFI Österreich, Wien.

WCED (1987). *Our Common Future*. Oxford, Oxford University Press.

Specific references

CHAPTER

Holmberg, J. & Karlsson, S., 1992. On designing socio-ecological indicators. In: U. Svedin and B. Hägerhäll-Aniansson (eds) *Society and Environment: A Swedish Research Perspective*, Kluwer Academic Publishers, Dordrecht.

CHAPTER 2

Karlsson, S., 1990. *Energy, entropy and exergy in the atmosphere*. PhD thesis, Institute of Physical Resource Theory, Chalmers University of Technology, Göteborg.

CHAPTER 3

Bringezu, S., Schütz, H., Behrensmeier, R. & Schmidt-Bleek, F., 1995. *Indicating environmental pressure for national economies and industrial sectors on the basis of integrated economic and environmental accounting*, Wuppertal Institute, Wuppertal.

Wernick, I. & Ausubel, J., 1995. National materials flows and the environment, *Ann. Rev. Energy Environ.* **20**, 463-492.

CHAPTER 4

Ayres R.U., & Ayres, L.W., 1995. *Materials cycles optimisation in the production of major finished materials. Chapter 1: Summary and overview*, Working Paper 95/05/EPS, Centre for the Management of Environmental Resources, INSEAD, Fontainebleau, France.

Holmberg, J., Robèrt, K.-H. & Eriksson, K.-E., 1994. *Socio-ecological principles for a sustainable society,* Report 94-11, Institute of Physical Resource Theory, Chalmers University of Technology, Göteborg.

Max-Neef, M., 1986. *Human-Scale Economics: the Challenges Ahead*, In: Ekins, P. (ed.), The Living Economy, Routledge & Kegan Paul, London.

Wernick I., Herman, R., Govind & J. Ausubel, S.,

1996. Materialization and dematerialization: Measures and trends, *Dædalus*, **155**, 171-198.

CHAPTER 5

Ajtay, G. L., Ketner, P. & Duvigneaud, P., 1979. In: *The Global Carbon Cycle*, Bolin, B., Degens, E. T., Kempe, S. & Ketner, P., (eds.), Wiley, pp. 129-181.

Alexandratos, N., 1995. *World Agriculture: Towards 2010.* FAO/UN and John Wiley & Sons Ltd., Chichester.

Azar, C., Holmberg, J. & Lindgren, K., 1996. Socio-ecological Indicators for Sustainability, *Ecological Economics* 18, 89-112.

Hall, D.O., Rosillo-Calle, F., Williams, R. H. & Woods, J., 1993. in *Renewable Energy: Sources for Fuels and Electricity*, Johansson, T. B., Kelly, H., Reddy, A. K. N. & Williams, R. H., Eds. Island Press, Washington, D.C. pp. 593-651.

Plucknett, D. L., 1993. *Science and agricultural transformation*. IFPRI Lecture Series, International Food Policy Research Institute.

SEI, 1990. Rijsberman, F.R. & Swart, R.J., (eds.), *Targets and Indicators of Climatic Change*. Stockholm Environment Institute, Box 1240, 105 14 Stockholm, Sweden.

World Resources Institute, 1994. *World Resources 1994-95.* Oxford University Press, New York/ Oxford.

CHAPTER 6

Galloway, J., W. Schlesinger, Levy II, H., Michaels, A. & Schnoor, J., 1995. Nitrogen fixation: Anthropogenic enhancement – environmental response, *Global Biogeochemical Cycles* **9**, 235-252.

Granstedt, A. & Westberg, L., 1992. *Växtnäringsflöden och natur-resurshushållning i svenskt jordbruk och samhälle – nuläge och framtids-möjligheter*, Department of Ecological Agriculture, Swedish University of Agricultural Sciences, Uppsala, Sweden. (In Swedish)

Kindbom. K. et al., 1993. *Beräknad ackumulerad syrabelastning från atmosfären till de svenska ekosystemen. Delrapport 1: Emissioner av svavel kväve ock alkaliskt stoft i Sverige 1900-1990*, IVL Report B1109, Swedish Environmental Research Institute, Stockholm. (In Swedish)

CHAPTER 7

Andersson, A., Gustafson, A., & Torstensson, G., 1988. *Utlakning av spårelement från odlad jord*, Swedish University of Agricultiural Studies, Uppsala Sweden. (In Swedish)

Crowson, P., 1992. *Minerals Handbook 1992-93*. Stockton Press, New York.

Nilarp, F., 1994. *Omsättningen av koppar i Sverge i ett bärkraftighetsperspektiv*. Thesis work. Institute of Physical Resource Theory, Chalmers University of Technology and Göteborg University, Göteborg, Sweden. (In Swedish)

Norrthon, P., 1996. *Sustainability and material flows - a study of the copper flow in Sweden*, Lic. thesis, Department of Physics and Measurement Technology, Linköping University, Sweden

Nriagu, J.O., 1990. Global metal pollution. *Environment* **32**, 7-32.

Skinner, B.J., 1987. Supplies of Geochemically Scarce Metals, In: McLaren, D.J. & Skinner, B.J. (eds) *Resources and World Development.* John Wiley & Sons, New York.

Tiberg, N. The Baltic Sea Environment, Session 10 The prospect of a sustainable society. The Baltic University Programme, 1992. p. 49.

A Sustainable Baltic Region

MAN AND MATERIALS FLOWS

Authors

Christian Azar

holds a Ph.D. in physical resource theory. He is at the Institute of Physical Resources Theory at Chalmers University of Technology and Götenorg University as are all the authors of this booklet. His research focuses on the economic aspects of the greenhouse effect, for instance, valuation of damage and conversion from fossil fuels to renewable energy. He has also worked on indicators for sustainability.

Göran Berndes

is a Ph.D. student in environmental sciences. His reseach is devoted to the societal conversion and use of organic materials for food, materials and energy.

John Holmberg

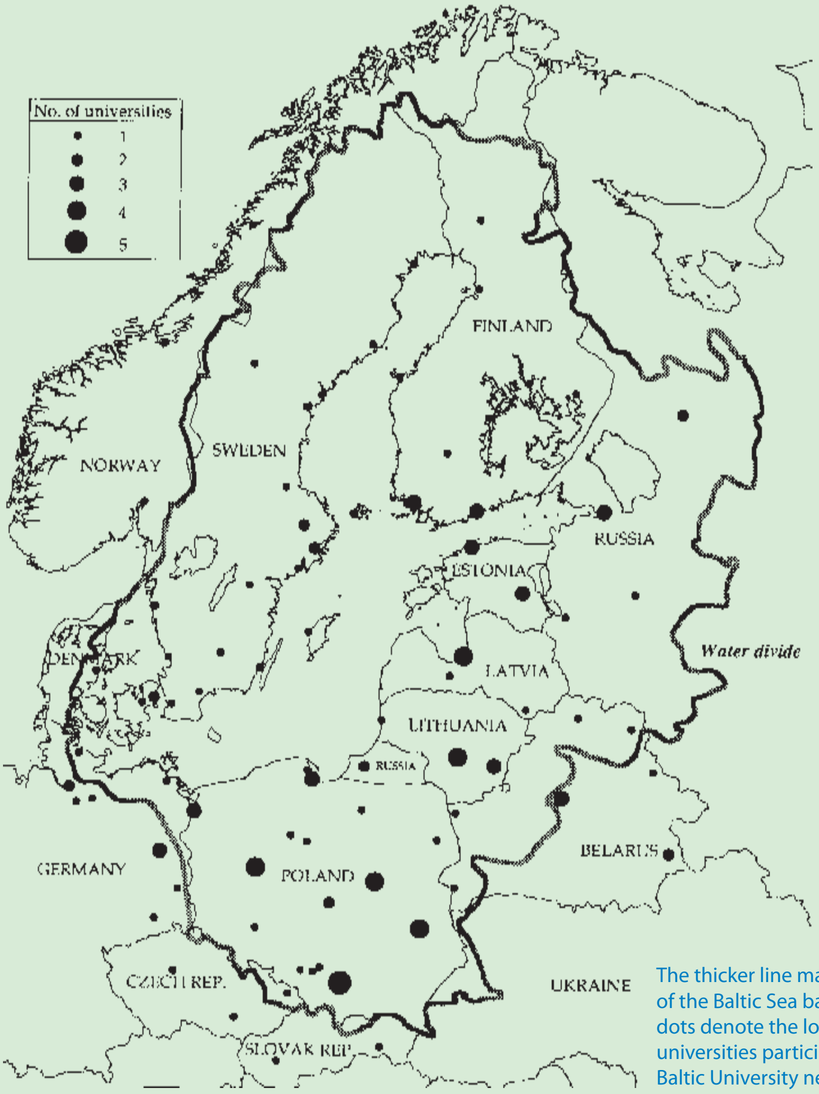
is assistant professor at the Institute of Physical Resources Theory. He has also worked on principles and indicators for sustainability. Currently he is directing a project aimed at developing strategies and scenarios for a sustainable energy future. He is a member of the board of The Natural Step Foundation, and scientific and strategic adviser and lecturer on the foundation's environmental courses.

Sten Karlsson

is a researcher at the Institute of Physical Resources Theory. He has worked on resource economics, energy systems analysis and atmospheric thermodynamics and is currently doing research on societal materials flows and adaption to long-term environmental and resource constraints.

Kristian Lindgren

is associate professor in physical resource theory. His field of research include energy scenarios, sustainability and complex dynamic systems. He is a member of the external faculty of the Santa Fe Institute, Santa Fe, NM, USA.



The thicker line marks the limits of the Baltic Sea basin, and dots denote the locations of universities participating in the Baltic University network.

A SUSTAINABLE BALTIC REGION is a series of well-illustrated booklets introducing the concept of sustainable development, in particular with reference to the area around the Baltic Sea, the Baltic Region. It deals with issues of sustainable use and management of natural resources, the long-term protection of our environment and the sustainable organization of human societies from the level of households to those of municipalities, cities and countries.

The booklet series constitutes the main reading in a university credit course, produced by the Baltic University Programme, and offered by the universities in the region. The other main component of the course is a TV series of ten programmes, produced in cooperation by a consortium of national TV companies in the region, broadcast over satellite TV and national TV channels. The TV series contains a wide variety of reportages from all count-ries in the region. In addition, the course contains a database on natural resources and environmental impact in the region available over the Internet. The booklet series is available in English, Polish and Russian, while the TV series is produced in English and in several national languages.

The Baltic University Programme is a network of international cooperation among some 150 universities in the 14 countries that are wholly or in part within the Baltic Sea basin. The Programme is coordinated by Uppsala University.

THE BALTIC UNIVERSITY PROGRAMME – UPPSALA UNIVERSITY

Address: Box 2109, S-750 02 Uppsala, Sweden
Tel +46-18-18 18 40 Fax +46-18-18 17 89
E-mail Baltic.Univ@uadm.uu.se

ISBN 91 7005 125 9