The Direct Material Inputs into Singapore's Development

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Summary

Because human population and socioeconomic activity are both increasingly concentrated in cities, an improved understanding of the environmental consequences of urbanization is needed. A 41-year annual time series of direct material flows was compiled for Singapore, representing a case of fast, export-driven industrialization. Results show that the spectacular economic growth of Singapore by a factor of 20 was associated with a similar expansion of domestic material consumption (DMC). DMC remained closely coupled to economic activity, increasing from below 4 tonnes per capita annually in 1962 to more than 50 tonnes annually in 2000. Despite economic structural changes and a growing service sector, no significant improvements in overall material productivity have been observed.

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Introduction

Urban centers share many functions of economic and industrial activity and high population density. They harbor about half of the global population on less than 3% of the terrestrial surface. For the subsistence of the population and to maintain the socioeconomic processes, they require large volumes of resource inputs from abroad, including materials for urban infrastructure development and maintenance. Those processes of resource extraction and consumption result in emissions to the air, water, and soil and are causing adverse changes in ecosystems increasingly on the global scale. Formally this balance of inputs and outputs had been described as urban metabolism (Wolman 1965; Boydon et al. 1981; Douglas 1983; Douglas et al. 2002).

It is understood that the environmental impact of cities differs considerably due to variable consumption levels, infrastructure technology, and geographical, historical, and cultural factors. Furthermore, economic development usually coincides with structural changes. Urbanization at low income levels was historically often associated with industrialization and a growing industrial manufacturing sector (Weber 1969; Bai 2002). Continuing economic expansion then often coincided with increased development of the service sector of the economy (tertiarization). Because the service sector produces intangible goods by definition and apparently requires fewer direct inputs of raw materials, it was suggested that this kind of restructuring contributes toward reducing environmental pressures. Additionally, rising urban density also harbors the potential for economies of scale and agglomeration, such as lower transport costs between producers and consumers and less demand for personal mobility. This trend again could contribute to decreasing environmental impact per capita with rising urbanization. On the other hand, life-styles, aspirations, and consumption patterns are also variable over time (McGranahan and Satterthwaite 2003; Liu et al. 2005; Ramos-Martin et al., forthcoming) and it is not well understood which of the dynamic factors prevails in development trends over time (Binswanger 2001). Because the global urbanization trend is ongoing and it is anticipated that

cities will grow by 2 billion people in the coming 25 years (UNDESA 2002), those questions deserve attention in the context of sustainable development.

To improve our understanding of these complex interactions, this article investigates economic development trends and environmental effects using the example of Singapore, one of the most dynamic economies over the past 41 years (1962–2003). Overall effects of the urban system on the environment are examined using direct materials flow analysis (MFA), a measure for the aggregate use of resources. One of the genuine methods of industrial ecology, MFA is based on the reasoning of a mass balance: what goes into the system as a resource must go out as an emission, or remain as a change in stock (Kleijn 2001a, 2001b). This way the method directs attention toward upstream activities in the life cycles of products and toward driving causes of resource depletion and generation of emissions. Furthermore, resource inputs are usually documented more comprehensively than outputs. Although studies of the energy system and carbon balances have attracted considerable attention in the area of urban environmental studies since the oil price shocks in the 1970s and again in recent years (Dhakal 2004; Huang and Chen 2005; Marcotullio et al. 2005), they are only one component in the larger system of urban metabolism. MFA additionally highlights the systematic interplay of energy carriers with other flows of biotic and abiotic resources. The central research questions of this article are how the composition and extent of material use are characterized on the urban scale, how this changes over time, and to what extent resource use and economic activity have been coupled over the past 40 years, because a de-linking of resource use and economic growth is considered essential for sustainable development in the long run.

This study presents an MFA for the city of Singapore. Although there have been expansion processes over the past 40 years toward a larger urban agglomeration (including bordering areas of Johore in Malaysia and Riau in Indonesia), this study assumed the constant spatial scale provided by the national border of Singapore.

Together with tools such as supply-chain analysis and physical input–output accounts (Suh

Table 1 Summary of economic data

		1965	1970	1975	1980	1985	1990	1995	2000
Population	[1,000 persons]	1,887	2,075	2,263	2,414	2,736	3,016	3,481	4,002
GDP	[\$/person]	2,667	4,439	6,430	9,058	10,764	14,365	19,157	22,741
DMI	[t/person]	8.6	16.3	18.0	22.7	27.8	33.4	37.6	75.1
DMC	[t/person]	3.3	6.8	8.3	9.9	14.6	13.1	17.6	53.8
GDP/DMC	[\$/kg]	0.81	0.65	0.78	0.92	0.74	1.10	1.09	0.42

Note: t = tonne; kg = kilogram.

et al. 2004), it is a contribution toward integrated economic–environmental accounting (UNDESA 2003). It emphasizes not only the embedding of urban economic activity in the global environment but also the role of cities in the international network of trade and flows of financial exchange (Moriguchi 2003; Decker et al. 2000; Castells 1996).

The article has four sections. The first introduces the context of Singapore and the phases of economic development planning; the second introduces the reasoning of materials flow analysis and methodological aspects; the third section discusses empirical results; and the fourth section finally draws some conclusions on the environmental impact of rapid urban transformation in the case of Singapore.

Phases of Planning and Economic Development

The small city-state on Singapore Island is well known for its dramatic economic ascent among the East Asian “Four Little Dragons”—newly industrializing economies (NIEs)—together with Hong Kong, Taiwan, and South Korea. It is an island and city-state without physical resources, except for its geographic location and natural harbor. Trade and transport services were therefore always at the heart of its economy. As a free trade zone, it succeeded in developing a strong export-oriented manufacturing industry including electronic products, information technology (IT) equipment, a petrochemical products industry, and, increasingly, a range of services from telecommunications and logistics to currency trading and other financial transactions. Despite having been criticized from outside for its interventionist economic policy and rigid

political system led by the People Action party (PAP), Singapore succeeded in expanding its gross domestic product (GDP) by a factor of 20 (GGDCCB 2005)¹ over the 41-year period between 1962 and 2003. Population grew from 1.75 million to more than 4 million and GDP on a per capita basis rose from 20% below the world average in 1962 to more than three times the world level in 2003, corresponding to the average GDP in the European Union (compare table 1).

Four phases of economic planning can be distinguished over the 41-year period under consideration. The first development plan had been outlined in 1960 with assistance from a UN mission (“Winsenius report”) and was primarily focused on job creation and establishment of the economic development board as the principal planning authority. It stayed in effect for 20 years through profound changes such as the establishment of Singapore as an independent nation after its initially joining the Malaysian federation in 1963 and separating from it in 1965, and the shocks in global oil supplies of 1973 and 1979. During this initial phase of economic development, manufacturing was the primary driver of growth in Singapore’s economy, and it succeeded in attracting many multinational companies (MNC) through its inexpensive work force and political stability. Environmental regulations were put in place at a very early stage of industrial development, with the foundation of a Ministry of the Environment in 1972 succeeding a previous antipollution unit under the prime minister’s office (Hui 1995). Besides land use zoning and transport development, the monitoring of air and water quality was introduced, and environmental concerns were increasingly prioritized in decisions on industrial extension (Rock 2002). Singapore also engaged in a strategy of

decentralized urban restructuring by creating a ring of dense, high-rise “new towns” with 400,000 units of public housing. Additionally, it started several massive infrastructure projects such as the new Changi Airport and expansion of harbor infrastructure, including oil and container terminals.

The second development plan was formulated by the Ministry of Trade in 1980, in a period when Singapore was facing labor shortages. It aimed toward improving skills and moving up the value chain of manufacturing industries. The phase also marks a transition in economic development, where the service sector started replacing manufacturing as the main engine of growth (Huff 1995). In 1984 the Singapore international monetary exchange (SIMEX) was founded, which developed into the fourth largest foreign exchange market in the world by 1993.

A third revised plan was prepared in 1985 by the Ministry of Trade and Industry in a phase of global instability, and after three years of an almost stagnant world economy. It aimed at further expanding the service sector to address threats of economic recession. Singapore had started to build an expensive mass rapid transit system (MRT) that started operation in 1987.

Finally, in 1991, the Ministry of Trade and Industry published the fourth, more visionary strategic plan, titled “Towards a Developed Nation,” somehow ignoring that the GDP of Singapore then was already nearly \$15,000 per capita following 25 years of growth above OECD average rates (see table 1). The 1991 plan formulated the aim to “attain the structure and characteristics of a first league developed country within the next 30 to 40 years” (Peebles and Wilson 2002, 5) and repeated aims laid out in the 1960 plan. Although the economy continued surging during the first six years of the 1990s, the Asian crisis in 1997 affected the entire region, as well as the collapse of the “new economy” in 2000 and the global recession in 2001. In 2003 the region was disturbed by the outbreak of the severe acute respiratory syndrome (SARS) virus, which affected the number of air passengers. By that time, the number of residential units under the housing and development board exceeded 850,000 units.

The 41 years of economic development launched Singapore into a privileged position in

the Southeast Asian region. Among the newly industrializing nations it attracted the largest volume of foreign direct investment and performed with the highest rate of economic growth. It was being praised as the most open and competitive economy in the world, although questions about the underlying growth mechanism were raised by some authors (Krugman 1994, Young 1995). As a founding member of the Association of South East Asian Nations (ASEAN), Singapore clearly contributed to a redefinition of the regional economy. Since 1990, Singapore signed numerous free trade agreements including the Asian Free Trade Area (AFTA) and contracts with the United States, Japan, the European Free Trade Association (EFTA), Australia, and New Zealand. Negotiations with seven more partners are currently going on. With an efficient legal and institutional system it became a preferred location for regional headquarters of multinational companies. Singapore’s stock market and international currency exchange benefited from its location in a previously uncovered time zone. In a similar way, its harbor benefits from its location in the Strait of Malacca, the principal gateway between the Indian Ocean and the South China Sea, a channel through which about 20% of global maritime trade passes. Singapore plans to expand its central position in financial and telecommunications markets and to diversify its service sector in the fields of education and biochemical, pharmaceutical, and medical research. Despite its comparatively small population, it is included among the leading group of world cities (Beaverstock et al. 1999).

Material Consumption Indicators

Studies of material flows on various scales are of genuine concern to the field of industrial ecology. An influential article in this context was a model for a hypothetical American city (Wolman 1965) that introduced the term “urban metabolism.” Empirical applications on the urban scale followed for Hong Kong (Newcombe et al. 1978; Boydon et al. 1981) and other cities (Decker et al. 2000; Tarr and Ayres 1990; Best Foot Forward 2002; Goree et al. 2000). Time series of material flow accounts, in contrast, have

so far been published mainly on the national scale (Adriaanse et al. 1997; Matthews et al. 2000; Eurostat 2002) and methodologies have increasingly been harmonized (Baccini and Brunner 1991; Eurostat 2001; Daniels 2002). The use of physical flow accounts has been proposed for indicators of integrated economic-environmental accounting on the national and international level (UNDESA 2003; Gravgard Pedersen and De Haan 2006). Some also suggest structuring accounts of the depletion of natural capital, as in the approach of “green GDP” or “genuine savings” (Lange 2003).

The account presented in this study is restricted to direct flows on the input side of the economic process. The term “direct flows” refers to resources used within the economic system of Singapore. Other authors have suggested that upstream flows that occur at earlier stages in the materials life cycle abroad, or material flows that do not enter the economic system, should also be included in the accounts. In the case of metal ores, for example, it would require the inclusion of volumes of overburden and mining waste; in the case of agricultural products, the associated topsoil erosion would be included; and in the case of imports, all those flows, including the physical costs of transport “from the cradle to the border,” would be used to calculate indicators of “total material use.” Although such accounts do cover a wider spectrum of environmental pressures, they also introduce new sources of imprecision. For raw materials, such factors can be established on a reliable basis, whereas for complex manufactured products, such accounts impose significant methodological difficulties.² Especially in open economies, where a mix of products is traded that were manufactured using different technologies, the databases for indirect flows are at best incomplete. Calculating such budgets in a time series approach would complicate the task even further. Although it should be kept in mind that on the aggregated level, indirect flows are often about the same as the volume of direct flows (and in individual material categories can exceed them by orders of magnitude), this study was restricted in scope to direct flows. This work could, however, be extended to include an assessment of indirect, embodied environmental pressures based on the established methodology.

This accounting was also restricted to the input side of the accounts. Balancing the changes in material stock and output indicators (Matthews et al. 2000) would require a different study design.

Methodology

To account for material input indicators, materials are distinguished by origin as domestically extracted (DE) or traded, that is, Imports (I) and Exports (E). The principal indicators used in this study are

Direct material input (DMI) = DE + I

and

Domestic material consumption (DMC) =

DMI – E

(Eurostat 2001).

Because primary industries played a less significant role in the highly urbanized economy of Singapore, the most important data source was the trade data. They were obtained from the United Nations Commodity Trade Statistics Database (COMTRADE) in the Standard International Trade Classification, revision 1 (SITC 1), on a 3-digit level. In the case of Singapore, this level of disaggregation produced annually reported imports and exports of 196 commodities representing more than 16,000 entries over the course of the 41-year period. At the 3-digit level, COMTRADE reports the transactions in monetary units (current value US\$) as well as in appropriate physical units such as tonnes,³ liters, and cubic meters. In this study, the physical data were utilized. They were considered more reliable than extrapolations of physical volume from monetary trade data, because they potentially include parts of the transport or insurance costs, and also, prices per volume vary considerably between regions and over time. The physical volume of all transactions was converted into units of weight using standard conversion factors. In a next step, the 196 commodities were aggregated to the 2-digit level, resulting in a reduction to 59 categories. Those items were grouped into 5 categories by dominating material properties (biomass, construction minerals, industrial

Figure 1 Import and export, physical flows.

minerals, fossil fuels) and into the heterogeneous category “semi- and final products.” With this operation, the total trade was summarized in 410 entries (5 categories, 2 trade directions, 41 years). Given the importance of Singapore’s port for the region, it is important to mention that transshipments, which dominate Singapore’s port activity (such as the redirecting of containers), are not included in the records on general trade and are therefore also excluded from this analysis.

Despite the dominance of trade in overall material flows, the domestic extraction of biomass and construction minerals proved to be significant as well, although during different periods in time. The principal data sources for land use and the domestic extraction of biomass were Food and Agriculture Organization (FAO) statistics and the statistical yearbook of Singapore. In the first 10 years of the time series there was still a considerable agricultural sector, cultivating about a quarter of the island surface. The dominating crops included fruits and vegetables as well as coconut, rubber, cassava, and sweet potatoes. Singapore still hosted a considerable livestock population. Biomass harvest statistics were obtained

from Singstat and FAO, and grazing of ruminant livestock was extrapolated from livestock numbers and literature values of fodder demand (Eurostat 2001). Quarrying for construction materials was the only mining activity in Singapore, as there are no deposits of ores or mineral fuels. The output from granite quarries for crushed and dimension stones had been reported in the USGS world minerals yearbook. This economic activity was also reported in the Singstat yearbook. Domestic extraction of sand was reported for several years, although it declined over time as domestic deposits on the relatively shallow island became exhausted. A further description of sources and conversion factors applied is documented in an earlier working paper (Schulz 2005).

Results

Figure 1 illustrates the spectacular rise in the physical trade volume of Singapore, reflecting the economic ascent and global market integration of the Southeast Asian region. Fossil fuels and construction minerals are the dominating material categories in terms of tonnage—a view quite

Figure 2 Domestic material extraction, trade, and consumption.

complementary to the monetary trade balance, which is clearly dominated by the value-intensive category “products.” Singapore established itself as the third largest refinery location in the world, after Houston and Rotterdam, and a preferred location for petroleum storage and trading in the region.

Figure 2 shows decadal trends of domestic material consumption (DMC = domestic extraction + imports – exports). They indicate a steady increase in weight of direct resource use per person from very low values, below 5 tonnes, to more than 30 tonnes per year. Furthermore, it is striking that an ever-larger share of direct material input (domestic material extraction + imports) is consumed as DMC in the system, whereas the relative weight of exports in relation to DMI declines. Nevertheless, the dominance of trade flows, exceeding domestic extraction by an order of magnitude, distinguishes the urban character of this MFA from typical nationwide accounts (Eurostat 2002).

Figure 3 shows annual values of DMC and their composition by material category. Appar-

ent is the interannual variation in material consumption, corresponding to regional and global economic events. In comparison to other industrialized economies (Adriaanse et al. 1997; Eurostat 2002), the initial level of per capita material consumption is exceptionally low, less than half the quantity of material used by other developed countries on a national scale. Throughout the time series the consumption of biomass stayed exceptionally low. Initially it was around 1.5 tonnes per capita and year, falling to values below 1 tonne per capita. This trend reflects the decline of previously existing remnants of plantation culture (such as copra and rubber) and the gradual abandonment of agricultural activity during the industrial transition and progressing urban development. It also reflects the externalization of food production chains and increasing dependence on ecosystem services from the hinterland, which extends to the entire globe, given the privileged location of Singapore on a global freight route. Urban metabolism’s dependence on rural areas is the underlying analogy of the ecological footprint

Figure 3 Domestic material consumption (DMC), Singapore.

concept (Wackernagel and Rees 1995). The domestic material consumption in the category of fossil fuels depicted a reverse trend. It started low, at about 1.5 tonnes per capita, and rose quickly to values above 10 tonnes, with substantial interannual variation. A closer look at energy balances (OECD/IEA various years) reveals that a significant segment of fuel consumption is located in the petrochemical sector due to refinery losses, which are inherent in the supply chain of fossil fuels. Only about a quarter of the crude oil imports of Singapore are consumed there; the majority are either exported after refining or sold as bunker fuel for international shipping or air transport.

The use of construction minerals showed even higher amplitude and volatility than fossil fuel consumption: it started at about 1.5 tonnes per capita and year and rose above 45 tonnes in the year 2000.

Construction minerals are the material category that is least reliably documented (Schulz 2005). Their uses are manifold: They include materials used for construction of housing, road infrastructure, industrial estates, airport enlargement, and the significant expansion of island area and waterfront development, a common strategy

of coastal cities for coping with increasing demand for limited land resources. Further attention should be given to the declining net imports of construction minerals in the three years after 2000.

The fourth category, “products,” consists of heterogeneous materials at advanced stages of processing into intermediate or final products. The product category carries more trading value than all other categories combined. The weight of imported products exceeded the weight of exported products for all years in the series by between 0.3 and 5.3 tonnes, except for the last year of the series, where this balance dropped to minus 0.02 tons per capita. The category involves semiproducts and final products, which are usually complex material mixtures including potentially harmful substances. They impose challenges to recycling and their safe disposal deserves attention (Williams et al. 2002; Berkhout and Hertin 2004). Relevant policy tools in this field include the concept of extended producer liability (e.g., regulations regarding the end-of-life management of consumer electronics and IT equipment), which is addressed by the broader concept of sustainable consumption

(Tukker et al. 2006). The relatively small share in weight of this category in relation to total material flows also indicates limits on the effectiveness of postconsumption recycling systems, because the streams of raw materials (that will generate waste during the production process) are significantly larger.

The overall amplitude of DMC from below 5 to over 50 tons per capita and year is reflecting a period of fundamental change and development: Also, the most recent years of the time series are interesting because they show a downturn in DMC. At this point, though, it is not possible to decide whether this reflects a turning point of a larger trend (possibly caused by successful establishment of required infrastructure) or an irritation due to temporary market insecurity. The ambitious plans laid out in the 2001 concept plan indicate a number of large-scale construction projects planned for the future.

Discussion: Material Use and Urban Development

Considerable effort has been spent in ecological and resource economics and development studies to better understand the general patterns or long-term trends between resource use, environmental pollution, and economic development (World Bank 1992; Munasinghe and Shearer 1995; Stern 2004). The underlying concerns involve the levels of resource depletion, environmental pollution, and encroachment upon natural ecosystems. Several international organizations emphasized the importance of decoupling resource use from economic development in the long run to achieve progress toward sustainable development (European Environment Agency 2003; OECD 2001; UNDESA 2003; Gravgard Pedersen and de Haan 2006). Although most empirical studies on aggregate resource use and economic development over time have been conducted on the national level, much less is known about those dynamics on the urban scale. In general, the role of cities in environmental change is seen as ambiguous. Some authors have emphasized the dependence of cities on ecosystem services far beyond their borders (Wackernagel and Rees 1995; Folke et al. 1997) or described cities as “parasites in the biosphere” (Odum 1971).

Others acknowledge their efficiency in housing a large population while providing economic and social development opportunities (McGranahan et al. 2006) or emphasize ecosystem services provided in urban areas (Bolund and Hunhammar 1999). The density of cities also offers potential for economies of scale in physical costs of infrastructure construction and maintenance. Additionally, structural changes in the economy can potentially contribute to reducing environmental pressures through expansion of the service sector, although this process sometimes just reflects the relocation of polluting industries (Bai 2002).

The empirical results on direct material consumption for Singapore, as presented in the second section, convey a mixed message: the initial period shows exceptionally low numbers for annual resource consumption, below 4 tonnes per person, which is about one-third of the value that is typical of other studies of industrialized countries on the national level or the average value of the 15 European Union countries known as the EU-15 (Adriaanse et al. 1997; Eurostat 2002). Very similar values have been reported in a classic study for Hong Kong for the year 1971 (Newcombe et al. 1978) and other urban scale studies in the literature (Schulz 2005). It is suggested that those values plausibly reflect some aspect of the urban density effect mentioned earlier. One more distinctly urban characteristic of this metabolic profile is the high contribution of imports to DMI and the large difference between DMI and DMC due to huge export volumes (compare figure 2). Similar values would be expected in other trading cities, such as Hamburg, Rotterdam, or Antwerp. In the case of Singapore, those initially low values of DMC rose very quickly to exceptionally high figures, above 50 tonnes per capita in 2000, which is more than for any of the 15 European Union (EU) countries in 1999 (European Environmental Agency 2003). Two factors are considered relevant to explaining this dynamic:

1. The small spatial extent of the study, which shows how concentrated human activities of resource use are in cities. The impact of individual construction activities would probably not be visible in a study on a national or international scale, such as one at the EU level. They would be buffered by the background flow of material use of the larger system. To illustrate the

Figure 4 Correlations between GDP, DMI, and DMC, Singapore 1962–2003.

concentration effect in Singapore, DMC can be related to the total extent of land area: Density values of DMC increased from 11 kilograms per square meter (kg/m^2) in 1962 to a peak of more than 300 kg/m^2 in 2000. This partly reflects the intensity of manufacturing processes, but also trends in verticalization of the urban morphology and infrastructure, as well as the active expansion of island area (Kog 2006).

2. The current process of urban development of high-rise buildings, road and rail infrastructure, airports, harbors, and land expansion is still going on in Singapore and is conducted with modern technologies that are capable of operating quickly and at large scales. In contrast to the developed country studies mentioned earlier, Singapore is undergoing a rapid and compressed growth phase that began about 40 years ago. The development and installation of physical infrastructure and other capital goods has probably taken longer (and was therefore conducted at lower growth rates) in the case of historically industrialized cities and nations (Douglas et al. 2002).

A decoupling between material use and economic growth could not be observed, and table 1 even indicates a decline of material productivity for the most recent figure in 2000.

Figure 4 shows high correlations of GDP with DMI and DMC. The relatively stronger correlation of GDP with DMI than with DMC is not surprising, given the importance of trade for Singapore's economy.

Because the spatial scale of the study was kept constant along the national boundaries of Singapore, possible policy measures to relocate polluting industries in response to urban environmental problems (Bai 2002) could not be observed if they would involve relocation beyond the national border. Within Singapore much emphasis was given to accurate planning and zoning (Wong and Yap 2004), and losing investments through relocations would have been against the interest of the national government. Although Singapore constantly expanded the capacity of some potentially hazardous industries such as the petrochemical complexes, no very large accident has been reported during the past 40 years. This might partly be attributed to the fact that most of the multinational companies originated in the United States, Japan, and Europe and were experienced at applying high quality standards and working under strict environmental regulations in those countries. Authors also described Singapore as the primary example of successful

pollution control in East Asia following a principle of “clean up while you grow,” rather than the pattern of “pollute now and clean up later” that could be observed in other countries (Rock 2002). Those conclusions were drawn based on empirical examples of production-related activities, such as ambient air pollution or trends in quality of surface water bodies. The results from the MFA indicate that this trend does not necessarily apply to consumption-related activities such as overall CO₂ emissions or solid waste generation (Bai and Sutanto 2002; Rothman 1998). In terms of material flows, Singapore appears to have followed trajectories similar to those of other industrialized countries. In accordance with its extreme rates of GDP growth, material consumption also turned out to be increasing at faster rates than those of historical examples of urbanization or industrialization (Schandl and Schulz 2002). Such observations are in accordance with urban environmental transition theory (McGranahan et al. 2006).

Conclusions

This study presented a time series study of urban metabolism for the case of Singapore to inquire into the environmental consequences of exceptionally rapid industrialization and urban transformation. As an ever-larger share of the worldwide population moves to cities, the consequences for urban resource demands need to be better understood. Although cities are promising with regard to returns of scale and of agglomeration, these developments also impose new pressures due to changing consumption levels and patterns.

This study could not find a tendency for a reduction in material consumption per unit of value generation or a delinking of overall resource demand from GDP. This occurred despite the fact that the MFA in this article was restricted to direct flow accounts and excluded hidden flows. Hidden flows are assumed to be relatively large in the case of Singapore, given the significance of trade in the urban metabolic profile. Also, the structural change from manufacturing-based growth toward an economy driven by the service sector since 1980 (Huff 1995) apparently did not affect material productivity (table 1).

Most MFA studies have been performed either for industrial countries that are net importers of raw materials (by weight) and can be described as centers of physical resource consumption, or for some resource-extracting countries, such as Chile or Australia (Giljum 2004), where the production and export of resources dominate the physical balance. Although the domestic market of Singapore provides a certain demand for resource consumption, the open and export oriented economic structure locates the overall system of Singapore much more at an intermediary position in the middle of global supply chains and trading interactions. With petroleum refining and the production of electronic components, computers, and information technology at its heart, Singapore's manufacturing sector is producing essential infrastructure components and fuels for advanced urban economies to maintain their “space of flows” (Castells 1996). In the service sector, Singapore is aiming to extend its position as a regional hub in financial services and to further develop its educational, research, and medical institutions. The trend in economic structure indicates further growth in the service sector, which is potentially less resource-intensive. The MFA presented in this study, on the other hand, indicates that Singapore's metabolism over the past 41 years was not “dematerializing” but rather just expanding, and it can be concluded that Singapore's economy still has considerable grounding in the biophysical world.

A persisting challenge for MFA remains the association of material flows with specific impacts, because the environmental effects (upstream and downstream of the consumption process) are very variable. The particular vulnerability of ecosystems differs with geographic factors, and the postconsumption impacts are very dependent on the applied technology of disposal. Nevertheless, the different material flow categories make it possible to identify pressures on specific ecosystems. Biomass use is linked to land use and pressures on terrestrial ecosystems (additionally, the pressures due to water demand for irrigation and leakage of agrochemicals into water bodies can be substantial). Although the bulk of construction minerals impose impacts of terrestrial and aquatic habitat destruction, industrial minerals typically involve very large hidden

flows and often inflict long-term risks due to mining tailings, leakage of acidic runoff, heavy metal contamination, and erosion. The life cycle of fossil fuels is associated with atmospheric emissions of CO₂, and upstream effects include emission of drilling sludge, tanker accidents, spills, invasive species associated with ballast water carried in oil tankers, and other social and environmental costs (O'Rourke and Connolly 2003). The category "products," finally, includes complex mixtures of materials that are difficult to separate or recycle. This material group imposes new and more complex risks when improperly discarded (Smith and Ezzati 2005). Alarming in this context is the changing stock of heavy metals and persistent organic pollutants contained in consumer goods. It calls for new regulations on how to handle electronic scrap through methods of extended producer liability or product stewardship, for example.

To address such cross-scale interactions on the global environment, further studies should make use of international, regionalized input-output tables to reflect variations in technology in countries of resource origin (Ahmed and Wykhoff 2003; Munksgaard et al. 2005). Accordingly, to address downstream effects in the recipient countries of trade, there is a need for harmonized databases on waste treatment technology and recycling (Hashimoto and Moriguchi 2004). Currently, for example, cross-scale effects and environmental costs due to embodied emissions, carbon leakage, or emissions from international transport are not reflected in international environmental or trading agreements. Considering the trends in international trade and market integration, this field deserves more attention.

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Notes

1. Comparisons are in 1990 international Geary Khamis dollars at purchasing power parity (GGD-CCB 2005).
2. Although life cycle accounts (LCA) have been established for many products, the applied accounting borders are usually case- and site-specific. In contrast to MFA studies, the spatial (origin of raw materials used) and temporal resolution (flows over a certain period of time) of such accounts are not at the focus of attention. The methodology of LCA is also not completely harmonized. LCA requires the application of cutoff criteria, for example, to which extent the physical costs of factors of production (costs for building the machinery, transport network and infrastructure development, etc.) are attributed to each unit of final product. One more argument is that total material flow indicators of subregions cannot easily be aggregated, because this would imply double counting of the hidden flows of products traded between those regions.
3. Tonne refers to metric ton. One metric ton = 1,000 kilograms (SI) = 1 Mg $\approx$ 1.1 short tons.

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