Material flows and resource productivity in China, Australia and Japan

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Summary

This paper presents material flow and resource productivity data and indicators for Australia, China and Japan for the period of 1970 to 2005. The main data used comes from a new material flows database for the Asia-Pacific region, which was assembled using up-to-date standardized methodologies, and which significantly extends the knowledgebase available for studies on resource use dynamics in the region. We show that the three nations studied here have diverging patterns of resource use, and that these patterns can be linked to interdependencies between them, and the very different roles each nation plays within a globalized system of natural resources exploitation. We also conduct a brief analysis of the most important drivers of changes in their resource use over the period, using an IPAT framework. The fundamentally different economic structure and trading roles of each country i.e. primary resource provider (Australia), mature and advanced manufacturer (Japan), and rapidly industrializing developing country (China), lead to starkly different contexts in which appropriate policies to encourage sustainable resources use must be formulated.

Keywords: Sustainable use of natural resources, resource efficiency, material flow accounting (MFA), trade, globalization

Introduction

Recent research on global material flows has shown rapid growth in the total amount of natural resources consumed globally, increasing from around 31 billion tonnes in 1975 to nearly 60 billion tonnes by 2005 (Steinberger, Krausmann et al. 2010), contributing to a myriad of environmental problems including deforestation, shortages of water, strategic materials, and food, and increased greenhouse gas emissions with their associated impacts on climate. These pressure points have converged recently in an unprecedented manner (Weisz and Schandl 2008).

Most of the growth dynamic in material flows has come from the Asia-Pacific region, especially since 2000, driven by the 'economic miracle' of China and its rapidly growing requirements for materials and energy, with associated growth in carbon emissions (Canadell, Quéré et al. 2007; Hashimoto and Moriguchi 2010; Schandl and West 2010).

Growth in natural resource use has been closely linked to globalization. The notion of globalization, according to Bauman (1998), acknowledges that the increasingly global nature of business, finance, trade and information flows is leading to ever more complex production-consumption chains. As a result of the globalization of economic activities, physical imports and exports of goods account for the fastest growing fraction of materials use. In many OECD countries, domestic extraction of materials has grown slowly or stagnated, while trade flows have continued to grow quickly (Weisz, Krausmann et al. 2006). A similar situation is revealed when the physical trade of many Asia-Pacific economies is examined.

In essence, this reflects the growing international division of labour, and spatial separation of production and consumption, made possible by the globalization of business. A national economy may outsource stages in the production of domestically consumed goods to other countries, thus externalizing some (or all) of the environmental burden associated with the production of those goods. The flip side of this is where a national economy specialises in producing specific goods for the world market, thereby internalising the environmental burden associated with external final consumption.

This increasing international division of labour and the increasing share of trade in servicing consumption have important implications for the definition of national resource use targets and indicators. This has been recognized in research that differentiates between production based and consumption based approaches to attribution of resource use and emissions (Hertwich and Peters 2009; Muñoz, Giljum et al. 2009).

The three nations examined here are taken as representative of three different types of countries within a six-category system of classification outlined in Krausmann et al. (2008).[1] This system is used in preference to some alternative earlier schemes, such as the division into core, semi-peripheral, and peripheral nations used in world systems theory (Wallerstein 1974) for a number of reasons. Perhaps the most important reason for preferring the six-category system is that it integrates physical factors such as population densities and natural resource endowment, which have been shown to have empirical links with patterns of resources usage. Different national patterns of resource usage can then be better placed in the context of the globalized economic system, while avoiding some obvious empirical shortcomings of earlier systems.[2] . This information is important for an informed policy debate on what would constitute a green economy, and low carbon development, at the global scale.

The national economies of China, Australia and Japan represent three of the different patterns of resource use, and as we will show in this paper, their respective patterns reflect their interconnections through trade. To determine the resource use patterns of each country, we used standard material flow accounting techniques to establish a set of headline indicators of natural resources use for each country. There has been earlier research on material flows for these countries including, most notably, Environment Agency Japan (1992), Moriguchi (1999) and Hashimoto et al. (2008) for Japan, Schandl et al. (2008), Schandl and Turner (2009) and Wood et al. (2009) for Australia, and the preliminary work of Chen and Qiao (2001) and more comprehensively (Xu and Zhang 2007) for China. Some authors, such as e.g. Bringezu et al. (2004) have presented data for China in an international comparison of resource use. The novel contribution of this paper is that we have used similar datasets and applied harmonised methods (based on EUROSTAT 2007) to come-up with comparable results for all three economies for a much longer and more complete time series than previously available.

We report trends in material flows and assess the economic efficiency of materials use over more than three decades and compare them to regional (i.e. Asia-Pacific) and global material use trends, then employ an IPAT framework[3] to quantify the relative importance of the main drivers of change in material use over the period, namely population, affluence and technology.

Three major questions arise from the observation of material use in Japan, China and Australia:

- How is it that Japan, already and by far the most efficient user of materials of all countries in the 1970s, has gone on to achieve the greatest proportional improvements in material efficiency in the decades since?

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[1] In this scheme, countries are classified according to their development status (developing and industrialized countries) and population density (low and high density with a cut off at 50 people per km^2). For low density a further distinction is made in regard to the settlement history ('old' vs. 'new' world). The authors show that the six resulting types display quite distinct metabolic profiles.

[2] A notable shortcoming of the core nation – peripheral nation classification system for application here is its failure to reflect current resources industry realities well, notably the implicit characterization of extractive industries as low capital and low skilled. Many of most successful primary resource exporters, particularly of energy and mineral resources, are notable for the dominance of large projects requiring extremely high capital investment, the deployment of advanced technologies, and with a high requirement for skilled labour.

[3] Impact = Population x Affluence x Technology (Ehrlich and Holdren (1971).

- Why has Australia's material efficiency remained effectively stagnant over the period examined?
- Which factors have driven the rapid increase in resource consumption in China, especially since 2000?

We aim here to highlight some factors that help answer those questions, and based on the analysis, highlight the need for policies to be harmonised at regional and larger scales to be effective in promoting sustainability in a globalized economy.

Methods and Data Sources

To analyse trends in material use and material efficiency in China, Australia and Japan we use a multi-dimensional dataset incorporating data from well accepted and accessible international data sources, to establish material flow accounts. The resulting time series cover more than three decades, from 1970 to 2005. In compiling the data we have adhered to the methodological guidelines set out in EUROSTAT (2007) as much as possible.

The material flow accounts calculated here take stock of natural resource inputs from domestic extraction (DE) or imported sources, covering biomass, fossil fuels, metals and industrial minerals, and construction aggregates, and also account for exports. We present a set of headline material flow indicators derived from these basic account elements, including physical trade balance (PTB) and domestic material consumption (DMC). A more detailed description of methodological decisions is available in Schandl and West (2010), with the data and a comprehensive technical annex available online at www.csiro.au/AsiaPacificMaterialFlows.

The measure of economic efficiency used for our analyses is resource intensity, i.e. DMC per unit GDP, with GDP specified in exchange rate base constant year 2000 $US from the World Bank (2009). The decision on which material flow indicator should be used to establish the efficiency indicator is not straightforward; however the textbook formula of GDP (Samuelson and Nordhaus 1995) includes the trade balance and so does DMC.[4]

It is important to keep in mind that the physical economy does not always parallel the economy as described in national accounts, so the interpretation of direct relations between physical and monetary data requires care (EUROSTAT 2001).

We use the well-known IPAT identity as an accounting tool for assessing the relative contributions of population (P), affluence (A) (or economic activity per person) and technology (T) to growth in domestic material consumption (I). We use population and per-capita income figures from the World Bank (2009). The Technology parameter is represented by DMC/GDP, i.e. material intensity, and is really a composite including all other drivers except population and income. T thus conflates the effects of technological change, innovation, and changes in economic structure and institutional arrangements that affect how technology is mobilized and economic changes are administered.

In this model, DMC = population * GDP/capita * DMC/GDP. We report raw percentage and absolute changes in impact (DMC), raw percentage changes in main drivers P, A and T, and also attribute changes in I to drivers using log transforms as described by Herendeen (1998). We do not use the evolved stochastic implementations of the IPAT model as done by, for example, Dietz and Rosa (1997) and York et al. (2003).

[4] The standard circular model of the economy shows that money and materials (or labour) usually flow in opposite direction in economic transactions. Therefore, the physical exports included in DMC are generally reflected in equivalent monetary imports (captured in GDP) and DMC is chosen as the most suitable physical equivalent of GDP.

Australia, China and Japan's roles in the global economy, and the implications for their resource use profiles.

China and Japan are among the four biggest trading nations in the world (by value), alongside the United States and Germany (COMTRADE, 2010). If we look at international trade flows for the three countries in 2005, we see that China imported $660 billion of goods and services, followed by Japan at $516 billion then Australia at $119 billion. Almost one third of all Japanese imports (by value) were primary materials including food, industrial raw materials and fuels. In comparison, only 17% of all Chinese imports and 8% of all imports to Australia were primary materials. China was also the largest exporter of the group in 2005, exporting goods and services valued at $762 billion, followed by Japan's $595 and Australia's $106. Around 43% (by value) of all Australian exports were primary materials, compared to 3% for China and 1% for Japan. This illustrates the very different roles these countries play in the world economy.

Australia's two most important trading partners are China and Japan, with 25% of all Australian imports for 2005 sourced from either China (14%) or Japan (11%), comprised mainly of final consumer goods, fuels, and capital goods from China, and transport equipment and capital goods from Japan. Both countries were extremely important markets for Australian exports. One third of all Australian exports in 2005 went to China (12%) or Japan (20%), two thirds of which were primary materials such as agricultural produce, iron, gas and coal. Note that Australia's dependence on commodity exports to these two countries has increased further since 2005.

China and Japan have also established strong trade interdependencies, with 15% of all Chinese imports in 2005 sourced from Japan (with capital goods responsible for 50% of those imports), and 21% of all Japanese imports coming from China (with goods for final consumption and capital goods the most important items). In the same year, 13% of all Japanese exports went to China and 11% of all Chinese exports to Japan. While Australia's economy depends on sales of raw materials to China and Japan, Australia has an only marginal share in trade, by value, from the viewpoint of China and Japan (constituting well under 5% of total trade flows). However, some of Australia's primary commodities could be strategically important from the point of view of China and Japan. For example, in 2008 Japan sourced over 70% of its thermal coal and 51% of metallurgical coal, along with over 50% of its iron ore from Australia, while China sourced over 40% of its iron ore imports from Australia (ABARE 2010).

While both Japan and China operate large manufacturing sectors and produce goods for foreign demand Australia's economy has focussed on its primary sectors of mining and agriculture with a marked decline of manufacturing over the last two decades. These very different roles in international trade played by the three countries have profound implications for the respective material flows profiles.

Figure 1 gives an indication of the relative importance of the three economies with regard to global resource use. The speed with which DE and DMC have grown in China, both in absolute terms and relative to Japan, is particularly noteworthy. China's aggregate DE increased from less than twice that of Japan in 1970, to over 22 times larger by 2005. This was due both to the extremely rapid growth in China's DE (CAGR of 7.1% for 1970 - 2005), and a considerable decrease in Japan's DE. Australia's DE went from being less than half that of Japan, to nearly double.

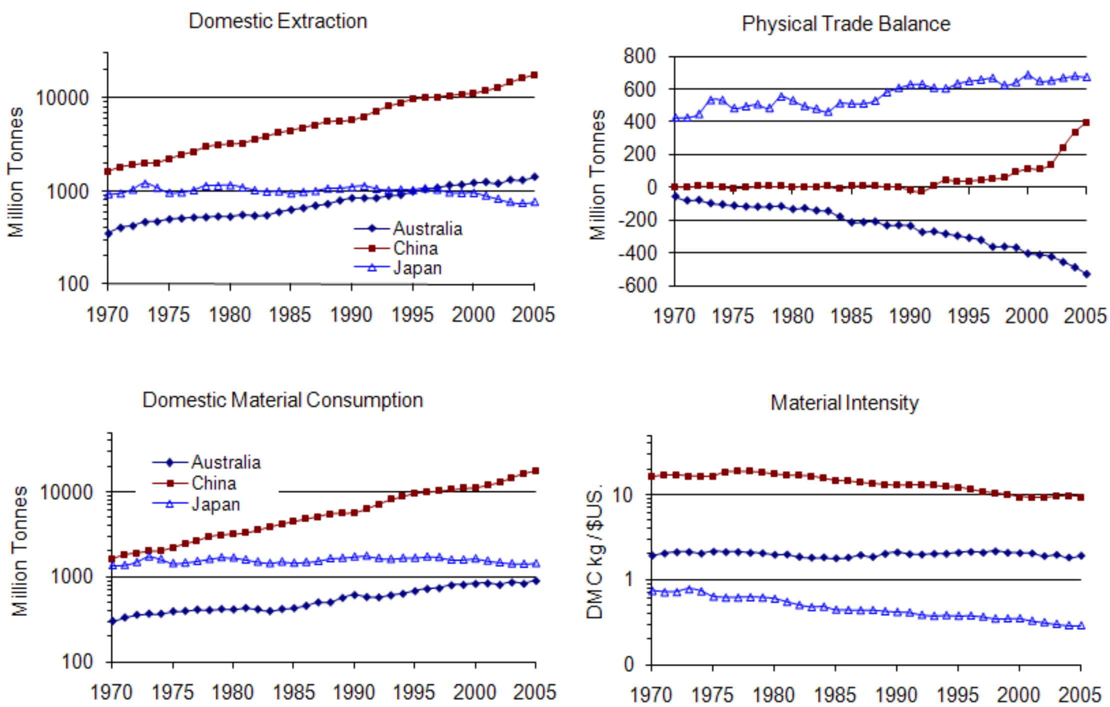

Figure 1 a-d: Three country comparisons of total DE, PTB, DMC, and material intensity

There have been similar but less pronounced changes in relative sizes of DMC over the same period. Japan's DMC did not decline over the full period, although it did decrease by nearly 20% after reaching a maximum of 1.76 Giga tonnes in 1991. China's DMC was 12 times that of Japan by 2005, after starting at around 1.2 times, while Australia's relative DMC grew from 22% of Japan's to around 62% over the 35 year period. Australia's more moderate growth in DMC relative to DE reflects the large degree to which increasing DE there went into net exports of primary and non-elaborately transformed commodities, which grew nearly tenfold over the period.

The massive dominance of China in terms of both DE and DMC has not yet been replicated in PTB. For most of the period China appears not to have been a major trading nation, instead being largely self-sufficient. It remained less important, in net trade volume terms, than either Japan or Australia throughout the entire period to 2005, never rising to more than 60% of Japan's level. The explosive rate of growth in China's PTB over the decade to 2005 indicates, however, that it may well be near or even have already exceeded Japan's net imports, which have been characterised by a slower, linear growth trend. The speed with which China is changing from relative self-sufficiency to being a net importer of materials has major implications for competition for global resources, as already demonstrated in the commodity price boom which preceded the Global Financial Crisis.

The final chart in figure 1 shows Materials Intensity (MI) in terms of total kg of DMC required to produce one dollar of GDP ($US on constant year 2000 exchange rate basis). While both Japan and China have increased the efficiency with which they use materials over time (with decreases in MI of approximately 60% and 40% respectively), Australia's efficiency did not improve over the entire period. How it is that Japan, already by far the most efficient user of resources in 1970, has managed to achieve the greatest proportional improvement in the decades since, while Australia's resource efficiency remained effectively stagnant?

To provide some insight here, it is desirable to first consider the underlying components of material flows in more detail and to observe the evolution of trade flows at that level. In figures

2 to 4, material flows are disaggregated into four major categories: biomass, fossil fuels, metal ores and industrial minerals, and construction minerals, all on a tonnes per capita basis to allow comparison among countries.

In Figure 2, the DE per capita profiles for the two industrialized countries, Australia and Japan, are starkly different in absolute size, and trend, and with regard to the shares of total DE occupied by each material category. The chart for Japan shows domestic extraction of all materials declining over time, from just under 9 tonnes per capita in 1970 to 6 tonnes in 2005, while Australia's DE grew from 28 to 70 tonnes over the same period. In Japan, the extraction of fossil fuels and metal ores was insignificant in 1970, and had almost ceased entirely by 2005. The exact opposite is true for Australia, with both categories combined accounting for around 50% of total DE in 1970, growing to over 75% by 2005. Japan's DE was dominated by construction minerals for the whole period, while for Australia construction minerals were always the least significant component. One point of similarity between the two countries is that the absolute size of construction materials DE per capita is similar for both, decreasing from 7.2 to 5 tonnes per capita between 1970 and 2005 in Japan, and growing slightly from 4.9 to 5.4 tonnes per capita for Australia. This similarity is significant, and discussed later.

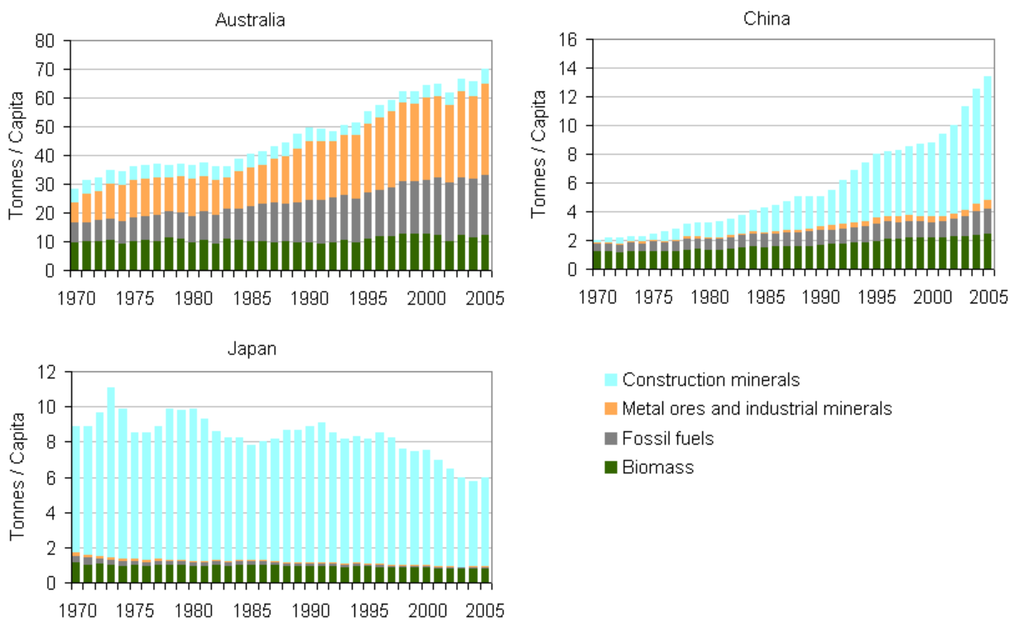

Figure 2 a-c Domestic Extraction per capita (note that y-axis scaling is not kept constant between countries)

The DE per capita profile for China starts from a much lower base than either Japan or Australia, then exhibits modest to extremely rapid growth for all materials categories, to the point where per capita DE reached more than twice that of Japan, although still only 20% that of Australia. It seems that agglomeration and density in Japan supports greater economies of scale. In common with Japan, China's DE is dominated by construction minerals, which at 8.6 tonnes per capita in 2005 far exceed contemporary levels in Japan (and approach Japan's high point of 9.7 tonnes per capita reached in 1973), and show a very strong growth trend. China shares rapid growth rates in DE of metal ores and fossil fuels with Australia, albeit at a much lower level per capita, whilst relatively strong growth in biomass extraction is unique to China.

Figure 3 summarizes net trade balances for the same four materials categories. Again it is the profiles for the two industrialized countries which are most starkly different to each other. At this level of aggregation, Australia has no net imports in any category, and is a large-scale exporter of metal ores and fossil fuels. In contrast, Japan requires significant net imports of fossil fuels, metal ores, and biomass.

China's chart is remarkable again more for the rate at which PTB has been changing. China progressed from very low levels of imports and exports at the start of the period, to become a significant net importer of metal ores and a new importer of fossil fuels. Even with metal ore imports still at a relatively modest 0.23 tonnes per capita, by 2005, China already eclipsed Japan in total tonnage of metal ore imports, and imported more than Australia's total (and very large) exports of metal ores.

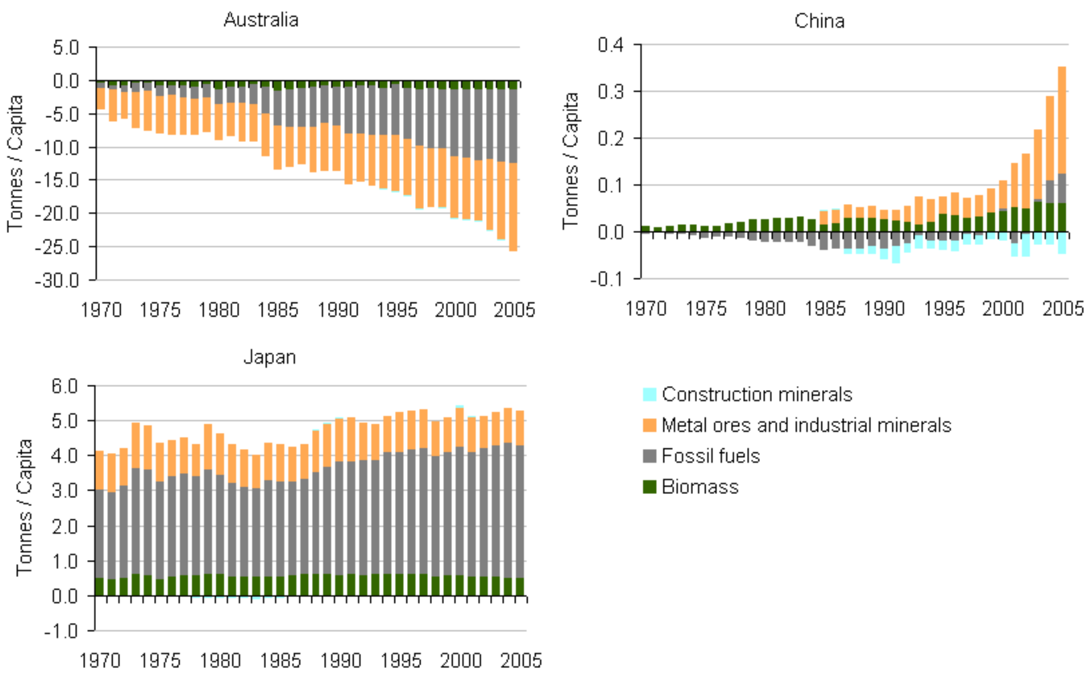

Figure 3 a-c Physical Trade Balance per capita (note that y axis scaling is not kept constant between countries)

Figure 4 shows DMC per capita. A noteworthy feature here is how little the chart for China differs from that seen in figure 2 for DE. Even though China's total imports were becoming quite large by 2005, they are insignificant compared to its total requirements. Even with respect to metal ores, around 70% of its demand was apparently still being met from domestic supply. In all other categories, China was still essentially self sufficient in net terms.

In contrast to this, the impact of taking trade into account is very pronounced for both Japan and Australia, with the former showing increases in total DMC over DE of 88% in 2005, mainly due to fossil fuels and metal ores imports, while Australia shows a decrease of 37%, almost entirely accounted for by exports of the same two categories.

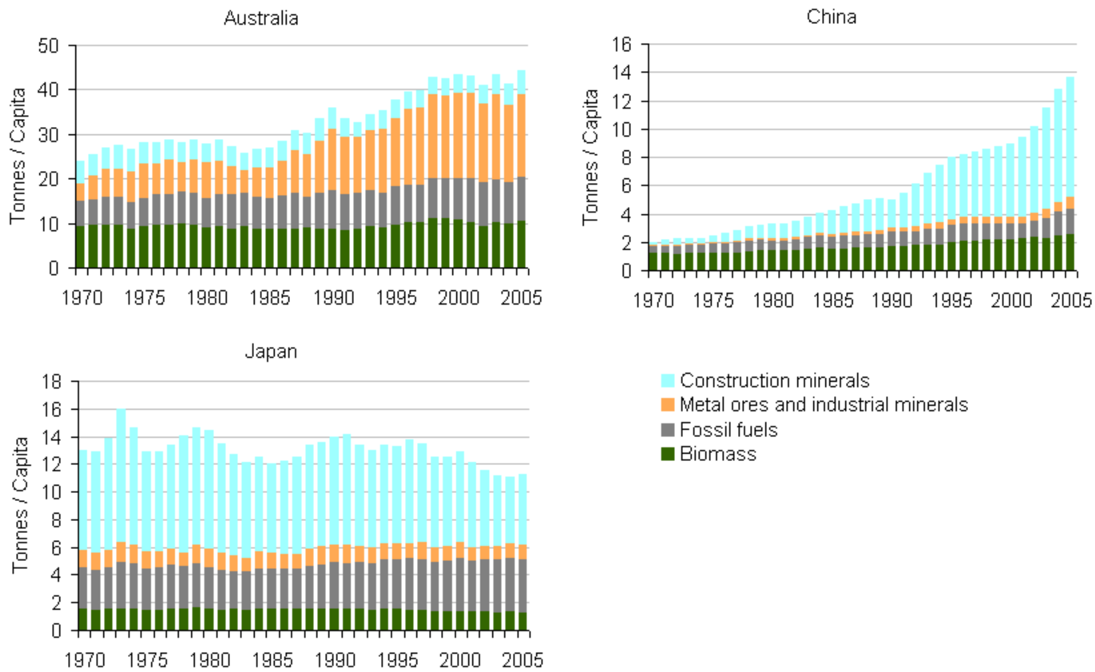

Figure 4 a-c Domestic Material Consumption per capita (note that y axis scaling is not kept constant between countries)

A key observation here is that even after PTB is subtracted from DE, the resulting figure for DMC will still tend to strongly over-estimate "final consumption" for exporters of metals and biomass, and under-estimate it for importers. This arises from the economy-wide material flow analysis (national) methodology used here (EUROSTAT 2001; EUROSTAT 2007) being largely blind to the original primary material volumes embodied in concentrated forms of traded near-primary commodities. This leads, for example, to all of the raw metal ore and fuel inputs required to produce a tonne of metal for export being attributed to the source country, whilst only the actual tonne of metal shipped is attributed to the importer and subtracted from the exporter's account.

Perhaps the most comprehensive method used to compensate for this problem is the calculation of raw material equivalent (RME) of imports and exports (Eurostat 2001; OECD 2008), which can then be used to calculate a figure for raw material consumption (RMC) in place of DMC. For recent examples where RME based measures have been calculated for different countries, see Muñoz et al. (2009), and Weinzettel and Kovanda (2009). Input-Output Analysis based methodologies were used for both of those studies (in the latter case refined in a hybrid application with LCI).

Unfortunately, the estimation of good RME values tends to be an extremely data and time intensive process, typically (to date) undertaken only for individual or small groups of countries and years. As a result, resolving material flows on a RME basis was not practical for the production of the base dataset on which this paper is based, which covers a large group of countries over a long and continuous time series. That being the case, it is possible to find other indicators that show that the very large difference in DMC per capita between Australia and Japan is largely a result of not accounting for the raw materials embodied in traded commodities.

The first line of evidence supporting this view is that, where scope for displacement of DMC is least, the difference in DMC between Japan and Australia is smallest. As noted before, the level of DE (and DMC) per capita of construction minerals is similar for both countries, with Australia using around 8% more than Japan in 2005. The most important (by volume) components of construction minerals, concrete aggregates and road base, are used in a form which retains most of the initial mass of the raw material as extracted, and so can't be imported in a highly concentrated form. Similarly, whilst there is considerable scope for displacement of DMC per capita of fossil fuels, e.g. via the energy embodied in concentrated metal exports, in many cases the form in which a fossil fuel is finally consumed retains much of the initial mass of the primary material extracted, e.g. liquid fuels and LNG. In 2005 Australia's DMC per capita of fossil fuels was 157% higher than Japan's. For biomass, where large quantities of grazed biomass and crop residues are often embodied in highly concentrated form as traded animal products, Australia's DMC per capita is over 700% higher than Japan's, whilst for metal ores, where concentration factors are often an order of magnitude or more between primary ore and traded commodity, Australia's DMC per capita is over 1,600% higher than Japan's. A rough indication of the ratios of raw materials embodied in their more commonly traded forms is provided in Table 1.

Table 1 Indicative ranges for the ratio of Raw Material Equivalent to traded commodities for different material categories

	Potential for concentration in traded commodities	**Indicative ranges of ratio of raw material to traded commodity**
Construction minerals	Low, especially for the volumetrically dominant category of construction aggregates.	1 - 2
Fossil fuels	Generally low where the traded commodity is a fuel, however can be very high if the energy embodied in concentrated commodities is considered, e.g. coal used to produce the electricity embodied in an aluminium ingot.	1 - 2 For fossil fuels traded as fuels or refinery feed stocks (excludes non-conventional petroleum).
Biomass	Low to high. While concentration factors of exported crops are generally low, traded animal products typically embody plant biomass one to two orders of magnitude greater than the traded commodity.	1 - 3 for crops and wood. 3 - 50 for animal products excluding whole milk.
Metal ores	Medium to extremely high	1 - 3 for ferrous metals, 3 - 300 for base metals, 10 - 2,500 for uranium, 5,000 - 2,000,000 for precious metals.

A second line of evidence indicating the degree to which Australia's apparent DMC in metal ores is final demand displaced from its trading partners can be inferred from a cross section of metal ore statistics. From ABARE (2010) the metal content in exports of (concentrated) primary materials, as a proportion of total metal content in minerals mined, averaged over the period 1990 - 2008[5], accounts for 79% of Australia's DE of copper, 91% of iron, and 97% each for

[5] A long-term average was used rather than a single year figure, as in the ABARE statistics metals contained in ore mined are frequently less than metal content of primary materials exported for a number of individual years. Some

lead and zinc. Yet only in the case of iron will these high levels of export make any significant reduction in Australia's apparent DMC (as iron ore is generally exported in a relatively un-concentrated form). The same data set enables to roughly calculate the percentage of metal contained in Australian DE which is exported to both Japan and China. The results are given in Table 2.

Table 2 Allocation of metal contained in Australia's domestic extraction of metal ores to destination country

	Iron Ore	Copper	Lead	Zinc
% Metal content in Australian DE not accounted for by exports (Australian domestic consumption)	9%	21%	3%	3%
% Metal content in Australian DE accounted for by exports to Japan	37%	20%	19%	8%
% Metal content in Australian DE accounted for by exports to China	37%	15%	8%	15%

Source: derived from ABARE (2010)

Again with the exception of iron, very little of this will show on Japan's or China's DMC accounts. It is also important to take into account that this metal is only that sourced from Australia. Both Japan and China source large quantities of metals from other countries. In a spot check on copper, it was found that if we take 3rd country supplies into account, in 2008 Japan actually imported copper equivalent to over 1.3 times Australia's total mine production. This means that Japan actually consumes slightly more copper on a per capita basis (around 110%) than Australia. This check was not performed for the other metals.

This provides a limited illustration, of a general point made explicitly or implicitly previously by others, i.e. knowing where accounting system boundaries are drawn, and where in the production chain accounting attribution takes place, is crucial for linking the environmental impacts of extraction to final consumption. With large scale international trade in concentrated forms of primary commodities, understanding the true load an individual economy places on natural resources requires that we look at the broader webs of trade in which that country participates.

Seen from this perspective, the extremely low materials intensity of the Japanese economy is not a realistic example for all other countries to follow, as the low apparent materials intensity of that country is largely accounted for by having materials intensive processes performed elsewhere, rather than doing away with them all together. Apparent dematerialization at the local level may do little to promote overall sustainability if it is achieved by increasing materials intensity elsewhere in the world system.

Another implication of the trade in concentrated primary commodities is that China's degree of self-sufficiency in metal ores is probably considerably lower than the apparent 70% referred to earlier. As is shown by a more detailed material category breakout), China had net imports of non-ferrous metal ores (and concentrates) equal to around 8.5% of domestic extraction in the same category, in 2005. As Table 1 and the discussion above makes clear, these imports will generally have had a much higher metal content per unit of weight than the domestically extracted portion, to the extent that it could well account for the majority of China's metals input.

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of this is presumably an effect of stockpiling, however, at least in the case of nickel some additional metal input to Australia comes from imports for which metal content is not recorded.

Drivers of resource use

The level of resource use in a country is driven by a number of factors. Here we use an IPAT framework to separate and analyse the role of three different drivers. This equation in its original form proposed by Ehrlich and Holdren (1971) conceptualizes total Impacts on the environment (I) as the product of Population (P), multiplied by the level of Affluence of that population (A), multiplied by a Technological coefficient (T). Here we define I = DMC, A = GDP/capita, and T = DMC/GDP.

Using this framework in its original form, determining the effect on I of changing an individual driver in isolation is straightforward. A 10% increase in P will, ceteris paribus, lead to a 10% increase in I. The situation becomes less clear where two or more of the drivers vary simultaneously, due to the multiplicative nature of the equation. Percentage changes in drivers (ΔP, ΔA, and ΔT) won't add up to give the correct percentage change in Impact (ΔI), and so it is difficult to allocate proportional "responsibility" for ΔI to the different drivers using IPAT in this form. A solution to this allocation problem is via a transformation of the IPAT factors to logarithmic form, giving an additive form of the IPAT equation where percentage contributions to the different drivers will add up to 100%. The results of applying this technique are shown in the last three columns of Table 2. The raw % changes in each driver are also shown, as in many cases interpretation of the raw change is much more intuitive and gives a better feel for the underlying dynamics[6].

Table 3 Drivers of change in DMC in Australia, China and Japan between 1975 and 2005

	Change in impact (DMC)		% Change in main drivers			Attribution to drivers using log transforms		
1975-1985								
	ΔI %	ΔI (mill. t)	ΔP	ΔA	ΔT	P	A	T
Australia	9%	37	13%	17%	-17%	140%	173%	-213%
China	103%	2,274	15%	99%	-11%	19%	97%	-17%
Japan	1%	12	8%	34%	-30%	895%	3432%	-4227%
1985-1995								
	ΔI %	ΔI (mill. t)	ΔP	ΔA	ΔT	P	A	T
Australia	59%	254	15%	19%	17%	29%	37%	34%
China	116%	5,195	15%	128%	-17%	18%	107%	-25%
Japan	15%	220	4%	31%	-16%	27%	194%	-121%
1995-2005								
	ΔI %	ΔI (mill. t)	ΔP	ΔA	ΔT	P	A	T
Australia	33%	221	13%	28%	-8%	43%	87%	-30%

[6] Details on the formulation of the log transformation of IPAT and a discussion of some limitations of the technique can be found in Herendeen (1998). The values for Japan over the 1975 – 1985 time interval illustrate one shortcoming of the method. In cases where we have large changes in drivers, of opposite signs, which have resulted in a small net change in *I*, we end up with very large % changes of opposing signs (which still add to 100%) to explain the small ΔI. Raw % changes do not suffer from this problem.

China	84%	8,162	8%	120%	-23%	13%	129%	-42%
Japan	-14%	-238	2%	10%	-23%	-12%	-61%	173%

Source: CSIRO and UNEP Material Flow database (2010) World Bank WDI database (2009)

Perhaps the single most important observation to be made based on table 2 is that China's extremely rapid growth in I has been overwhelmingly driven by growing A, in each of the three decades analysed. P has been a relatively minor and decreasing contributor to growth in I, whilst T has consistently acted to moderate growth in I, and became progressively more effective in this role with each successive decade. Unfortunately, the moderating effect of T has never been sufficient to offset even one third of the growth driven by A in any single decade. As increasing material standards of living is a major goal behind China's push for industrialization, the major driver of China's rapid growth in DMC looks likely to continue undiminished.

Affluence has in fact been the most important driver of increasing I in the industrialized countries as well, albeit acting at a much more moderate rate. The role of P has varied, having been a relatively insignificant driver in both Japan and China, whilst in Australia it has consistently had 50% or more as strong an effect as A. In all but one case (Australia from 1985-1995), T has acted to moderate growth in I, however only in the case of Japan for the decade 1995-2005 has it been sufficient to counteract the effects of very modest contemporary growth in P and A, causing I to actually decrease in absolute terms.

It is important to emphasise that big T technology as used here is specifically defined as simply DMC/GDP, so an improvement (decrease) in T is not necessarily linked to efficiency improvements in specific process technologies. An economy which changes its relative mix of industrial sectors, outsourcing the more material intensive sectors to other countries, should show an improvement in T. In light of the previous discussion of the trade in concentrated primary commodities, some of the improvement in T for Japan may well be accounted for by such industrial displacement. Another factor that may strongly affect T, without any change in the underlying physical technologies, is fluctuating exchange rates.

Discussion

Table 3 shows high-level economic development, demographic and resource use trends for the three countries and compares them to regional and global trends.

Table 4 Comparison of resource use and economic development trends in China, Japan, Australia, Asia-Pacific and the world

	World (Krausmann)	Asia and the Pacific (Schandl and West, 2010)	China	Japan	Australia
DMC, million tonnes	59,474	35,289	17,838	1,433	901
DMC/capita, tonnes	9.3	9.0	13.7	11.2	44.2
ΔDMC (1970-2005), %	2.3	3.4	7.1	0.17	3.2
GDP, billion $	36,568	10,733	1,890	4,942	472
GDP/capita	5,662	2,750	1,449	38,690	23,141
ΔGDP (1970-2005), %	3.2	3.8	8.8	2.9	3.2
Population, million	6,458	3,902	1,304	128	20
ΔPopulation (1970-2005), %	1.6	1.5	1.3	0.6	1.4

DMC/GDP, kg per $	1.63	3.29	9.44	0.29	1.91
ΔDMC/GDP (1970-2005), %	-0.89	-0.38	-1.53	-2.68	0.0

Source: CSIRO and UNEP Material Flow database (2010) World Bank WDI database (2009)

Of the three countries, Japan has had the lowest average economic growth and population growth, factors contributing to its very small increase in DMC in recent decades. Also, as an HDI type country in the typology laid out by (Krausmann, Fischer-Kowalski et al. 2008), it has have a long history of agricultural development and industrialization, developed high population densities, and has a relative scarcity of natural resources (both sources of raw materials and sinks for waste products). These factors have long encouraged efforts to use resources more efficiently, and placed a premium on recycling activity, to decrease dependence on imported raw materials. The positive effects of this on resource efficiency have been further enhanced by the opportunities globalization provides for large-scale outsourcing of primary extraction activities, as outlined in the analysis above. This has earned Japan an efficiency dividend, enabling the most material efficient economy to raise its initially high efficiency even further, going from an MI of 0.75 to 0.29 kg per US$ over the period.

Australia has had an intermediate rate of economic growth and the highest rate of population growth of the three countries. It has by far the highest DMC per capita, although its rate of growth in DMC has been less than half that of China. While Australia and Japan enjoy similarly high standards of living, Australia is at the opposite end to Japan in the functional division in the global economy. As an LDI-NW type country, it is characterised by large available land area, a relatively short history of intensive agriculture (with low population density as a result), and a rich endowment of natural resources. With a small domestic market and a shrinking (in relative terms) manufacturing sector, Australia's economy has become ever more reliant on the export of large and increasing volumes of raw materials and non-elaborately transformed commodities such as coal, iron, aluminium, wheat and beef. For the reasons outlined in the analysis above, in providing large amounts of primary resources in concentrated form to other countries, including Japan and China, Australia necessarily incurs very high apparent material use, which flows through to poor relative trends in material efficiency. This is evident in the stagnation of MI at 1.9kg per US$ for more than three decades. This has been exacerbated by the continuing high consumption lifestyle of the average citizen.

China displayed an extremely high rate of economic growth over the period, a modest rate of population growth, and a very rapid rate of growth in DMC. As DMC grew more slowly than GDP, a degree of relative dematerialization in the Chinese economy, with MI decreasing by 1.53% p.a. over the period has occurred. Despite this relative dematerialization, DMC per capita now exceeds that of Japan, despite China having a much lower standard of living. Most of this can be explained by the fact that China is one of the HDD type countries undergoing very rapid industrialization. As HDD countries begin this process with a relatively large agricultural sector, low living standards, and high population densities, massive quantities of materials are required build sufficient infrastructure to effect the transition to industrialization. This is reflected in the degree to which construction minerals dominate DMC. Another contributing factor is that, while China has outsourced a portion of its primary production functions, overall demand is so great that it is simultaneously expanding virtually all sectors of domestic resources extraction, incurring the large materials flows associated with those activities.

Policies that may guide sustainable material use

We have shown that the Japanese economy has been a showcase of highly efficient material use over the last few decades, one of the few OECD countries to avoid a significant increase in the total tonnage of natural resources required to fuel its economic development.[7] While an important factor in achieving Japan's high resource efficiency has been the outsourcing of material intensive processes overseas, it also reflects major political efforts to control resource use and waste. Japan has been instrumental in driving the 3R (reduce, reuse, recycle) agenda internationally, through the Group of Eight (G8) and the OECD, and domestically has the high-level policy principle of a Sound Material Cycle Society (SMC Society) (Takiguchi and Takemoto 2008). The fundamental law to establish a SMC society was enacted by the Japanese parliament in 2000. It has been operationalized in a set of 3R policies. These policies integrate the promotion of effective and efficient utilization of natural resources with waste management principles, and have led to explicit targets for achieving resource efficiency. These targets include a 60% improvement in resource productivity by 2010, a 40-50% increase in the recycling rate, and a 60% reduction in the amount of waste disposal. These ambitious policies are likely to have contributed to Japan's success in reducing natural resource use, but it is important to note that Japan has also endured a long period of economic stagnation, which in itself must have helped it achieve its ambitious environmental goals.

China has also set a number of policy initiatives and targets for improving resource efficiency, including targets laid out in the 11th Five-Year Plan (Schandl, Alexander et al. 2011). These targets include reducing energy consumption per unit of GDP by 20% over 2005 levels (ESCAP 2007). There are also ambitious policies aimed at increasing recycling of precious metals, and reducing waste and emissions. Such objectives are hard to achieve in a situation of rapid economic growth, underpinned by a massive expansion in transport infrastructure, manufacturing plant, and the new commercial and residential buildings required for rapid urbanization (Schandl, Fischer-Kowalski et al. 2009). Rapid growth in the numbers of new, middle-class consumers in western China (Myers and Kent 2004) will further exacerbate the task required of policy makers. The ongoing rapid transition of China from an agrarian socio-metabolic regime to an industrial regime has had a clearly discernable impact on global resource flows, most apparent in the consumption rates of strategic industrial inputs such as iron and steel, coal, cement, and paper, where China has emerged as the largest user globally (Hashimoto and Moriguchi 2010).

China's aims for sustainable resource use should be viewed in the context of its need to alleviate poverty, raise the standard of living of its large population, and meet the rising aspirations of its people.

Australia faces a very different set of challenges to those confronting Japan and China. A combination of factors has contributed to its very high levels of per capita resource use. These include the pivotal role of export oriented primary industries in its economy (metal ores, coal, gas, and agriculture), the large physical area and low population density of the country (which increases infrastructure requirements per capita), a very high reliance on electricity generation technologies characterised by high fuel inputs, poorly developed public transport in most cities, low energy efficiency and high operational energy requirements of much of the housing stock, as well as the generally high consumption lifestyle of its population (Schandl and Turner 2009). Current global economic trends suggest that Australia's resource use will increase further, driven by the 'resource hunger' of China and to a lesser extend Japan. It is challenging to formulate and implement policies to increase the efficient use of natural resources in an economy so dependent on primary industries to provide both jobs, at the regional level, and to provide export income and taxes at the national level. While there is an aim to rise the share of renewable energy to 20% by 2020 there is still a lack of coherent policies to drive increasing resource efficiency, and inadequate information systems to inform such policies.

[7] This is correlated to low population growth and an aging population resulting in reduced overall labour volumes.

As we have shown, national material use is highly interconnected in modern economies, with globalization creating intricate networks of material dependencies among countries. It is no surprise that international organizations are moving to recognize this fact in their strategies and programs to promote green growth and sustainable consumption and production. For Asia and the Pacific, the United Nations Economic and Social Commission has promoted green growth, a comprehensive set of guidelines aimed at keeping social and economic development within resource and ecosystem limits, since 2005. A summary of ESCAP's most recent assessment is provided in the preview of their 2010 sustainability report (ESCAP, ADB et al. 2010) which was launched at the Ministerial Conference of Environment and Development (MCED) in Kazakhstan in October 2010.

There is still a long way to go in developing the institutional capacity and information systems required to provide adequate indicators of the state of the "physical economy". These indicators are nonetheless an urgently needed complement to the basic economic indicators such as GDP, trade balance, inflation and unemployment rate which currently dominate economic decision making. Only such physical indicators can show the rate at which loads on natural resources are increasing and shed light on the ongoing physical sustainability of current economic systems. .

Conclusions

In this research we aimed to understand why material efficiency has improved in Japan, and why it stagnated in Australia over the last few decades. We were also interested in unpacking the tremendous growth in material use in China during this time. We have used material flow and resource productivity data and indicators to analyse trends over the period, and have looked at how the different metabolic profiles were interconnected through international trade. We have also used an IPAT framework identify the relative importance of population, affluence and technology in driving the growth in materials use. . Finally, we characterised the metabolic profiles of the three economies – China, Japan and Australia – within a scheme proposed by Krausmann et al. (2008).

The major improvement in material efficiency in Japan stem from a number of factors. These include the outsourcing of material intensive primary industries to other countries and relative economic stagnation over much of the last two decades, but also reflect the set of very ambitious environmental policies enacted which encourage reduced materials throughput, reuse of materials, and recycling.

Australia has been at the opposite extreme, greatly increasing output from its largely export oriented primary industries – agriculture and mining – over the last three decades, leading to ever increasing materials use and stagnant materials efficiency. Australia, because of the nature of its production system might not be able to achieve economies of scale. At the same time, the existence of export orientated extractive economies like Australia enables importers of concentrated forms of raw materials such as Japan to avoid the bulk of the environmental loads associated with extractive industries, yet still receive the full benefit from their consumption. Of course, the attribution of final consumption is even more complicated in practice, given the trade relationship between Japan and Australia. While Australia exports iron ore and coal to Japan, it imports vehicles and consumer goods in return, and is thus the place of final consumption for the raw materials embodied in those goods. Nevertheless, given the small proportion of Japan's total exports accounted for by Australian imports, it is virtually certain that if all primary materials were attributed to the point of final consumption, total material use and material efficiency in Australia would improve considerably, and Japan's would deteriorate.

China is an interesting and vitally important case in itself due to the sheer scale and speed of transformation of its economy, creating a huge demand for ever more resources. Already the single biggest material user globally, the underlying trend indicates continued and rapid future growth. Despite its rapidly increasing materials use, driven by industrialist economies, the country has invested in material and energy efficiency and has agreed on a set of policies similar to Japanese efforts aimed at achieving more sustainable resource use in the future.

This study of three linked economies in the Asia Pacific region supports the argument that, as economies become increasingly interdependent through the processes of globalization, efforts to improve the sustainability of materials use will need to focus on initiatives effective at scales larger than the individual nation state. It also provides a limited illustration of the huge difference in scale and nature of development questions facing the individual constituent nations for this one highly interdependent three country sub-system. Developing transnational initiatives which reconcile the aspirations of the bulk people of the Asia–Pacific region for higher material standard of living, with the need to keep resource use and environmental impacts within sustainable limits, promises to be extremely challenging.

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