A Material History of Australia

Evolution of Material Intensity and Drivers of Change

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:// Supplementary material is available on the *JIE* Web site

Summary

This article presents an analysis of the material history of Australia in the period 1975–2005. The values of economy-wide indicators of material flow roughly trebled since 1975, and we identify the drivers of this change through structural decomposition analysis. The purpose of this work is to delve beneath the top-level trends in material flow growth to investigate the structural changes in the economy that have been driving this growth. The major positive drivers of this change were the level of exports, export mix, industrial structure, affluence, and population. Only improvements in material intensity offered retardation of growth in material flow. Other structural components had only small effects at the aggregate level. At a more detailed level, however, the importance of the mineral sectors became apparent. Improvements in mining techniques have reduced material requirements, but increased consumption within the economy and increased exports have offset these reductions. The full roll out of material flow accounting through Australian society and business and a systematic response to its implications will require change in the national growth focus of the last two generations, with serious consideration needed to reverse the current volume-focused growth of the economy and also to recast neoliberal and globalized trade policies that have dominated the globe for the past decades.

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Introduction

It is commonly believed that the increasing activities of a consumption-hungry industrial system have been driving the increases in Australia's environmental impact. Indeed, in Australia's case, the natural environment is linked to the industrial ecology, but ultimately—via quite complex production chains—to the consumption of an affluent population. Changes in any part of the production structure will result in changes in overall environmental impact. For example, even if consumption increased, net environmental impact may not worsen if industrial efficiency of natural resource use improved at the same time. Therefore, the knowledge of these environment-economy linkages, and their historical trends, can direct policy to be most effective.

This study seeks to understand changes in the factors that influence material flows by taking a historical perspective to the determinants of growth in the material intensity of Australia. We undertake an investigation of structural changes in the economy over a period of 30 years (1975–2005). A detailed structural decomposition model is developed using input–output analysis (IOA) at a sector level of 344 industries. This level of detail was selected to enable continuity over the series of input-output (IO) tables and disaggregation of environmentally important industries. Such disaggregation is important in order to not lose track of changes when industries with very different extractive processes are grouped together.

The use of IOA in studying environmental effects stems from the late 1960s (see Daly 1968; Isard et al. 1967; Ayres and Kneese 1969; Leontief and Ford 1971). Its subsequent use in structural decomposition analysis (SDA) initially focused on energy use (Proops 1988; Rose and Chen 1991; Chen and Rose 1990) and greenhouse gas emissions (Casler and Rose 1998; Common and Salma 1992; Proops et al. 1993; Wier 1998; Chang and Lin 1998; De Haan 2001; de Nooij et al. 2003).

The work documented in this article updates MFA studies on Australia by Poldy and Foran (1999) and complements the work of Schandl and colleagues (2008). Further, to the knowledge of the authors, the only published applications of SDA in the Material Flow field is the total material requirements analysis for West Germany[1] and an analysis of Chile (Muñoz and Hubacek 2008). Hoffrén and colleagues (2001) and Hashimoto and colleagues (2008) analyze material flows, but, instead of SDA, these authors use index decomposition analysis, a decomposition variant that does not investigate the technological relationship between industries. Our data set is the most detailed extended IO data set that we know of in Australia and the only existing time series. We extend Moll's methodology by incorporating recent work on index decomposition (for an introduction, see Ang et al. 1998; Ang 2004). We use the adaptive weighting of the logarithmic mean divisia index (LMDI) to enable a perfect decomposition (i.e., leaving no residuals), with correct handling of zeros in an SDA context (Ang and Liu 2007; Wood and Lenzen 2006).

As the purpose of this work is to delve beneath the obvious trends in material flow growth to investigate the structural changes in the economy that have been driving this growth, we perform a decomposition analysis to reveal the influence of material intensity changes, affluence and population growth, structural changes in the economy, and the effects of final demand level, mix, and destination. The results of our work demonstrate to policy makers the practical utility of combining MFA with SDA. For example, we explicitly take into account changes due to variations in exports so that policy makers can consider material consequences of international trade in their decisions.

The basic methodology and sources of data of this study is included in the next section. Results of the decomposition for Australia's material flow from 1975–2005 follow. In a far-ranging discussion we place these results in the theoretical and policy context by describing tangible and relevant implications for business and government. Conclusions then round out the article.

Methodology

Material Flow Analysis

MFA has gained momentum since the early 1990s with the ConAccount research network[2] (Bringezu et al. 1997; Kleijn et al. 1999), followed

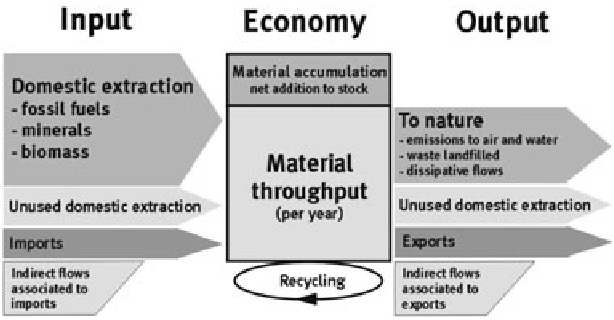

Figure 1 General scheme for economy-wide MFA, excluding water and air flows. *Source:* EUROSTAT (2001).

by the World Resource Institute cross-country studies (Adriaanse et al. 1997; Matthews et al. 2000). Standardization was achieved through the publication of a methodological guidebook by the European Statistical Office (EUROSTAT 2001), and subsequent development in the field is summarized by Weisz and colleagues (2007).

There are a number of definitions applicable to MFA (figure 1). *Domestic extraction* (DE) and *direct material consumption* (DMC) are calculated directly from production, import, and export statistics (as defined in Weisz et al. 2007). DE is the mass of material entering the economic system without including any unused extractions (domestic or imported) or the flows associated with imports. In comparison, DMC is the actual material consumption of the population, including imports and excluding exports. We also must define a third indicator, *direct material intensity* (DMI), in this study to allow incorporation of both imports and exports within our analytical system (we return to this later). In contrast to these direct indicators, a fourth indicator, *total material requirements* (TMR), is defined as the summation of all material flows required for a population (EUROSTAT 2001). This includes material that enters the economic realm as well as “unused” flows—which are the necessary displacement of material for an auxiliary purpose (e.g., the creation of tailings associated with mining). Estimations of unused flows are important for three reasons. First, in a macrosense they define the physical “overhead” of an economic system that in many circumstances characterizes an economy’s sophistication with regard to how efficient it can process its resources. Second, the unused flows in farming are important ecologically as the soil erosion component impacts negatively on long-term sustainability. Third, for mining, high levels of material flow often reflect declining ore grades and increasing requirements for mine rehabilitation services once the core product has been extracted.

Direct imports are included, and indirect impacts and unused flows associated with the imports are also included in TMR. Poldy and Foran (1999) argue against the inclusion of unused flows in imports to avoid double counting in intercountry analysis. As the availability of data on unused extraction for Australia’s import partners is very low, in this study, the intensity of unused extraction embodied in imports is assumed to be the same as domestic production. For Australia, imports are reasonably minor, and of these imports, relatively few are from primary industries with materially large unused extraction associated; thus, there is likely a negligible distortion on final results.

The only deviation we take from the current standards (Weisz et al. 2007) is that we exclude calculation of grazed biomass as a component of domestic extraction; however, all fodder is still included.[3]

Input–Output Analysis

IOA is a top-down macroeconomic technique, which uses sectoral transaction data to account for the complex interdependencies of industries in modern economies. Generalization of the basic formulation of IOA for physical factors (such as material flow) yields so-called *factor multipliers*, that is, embodiments of the physical factor per unit of final demand of commodities.

Mathematically, a multiplier matrix $\mathbf{M}$ is calculated from a $1 \times n$ matrix $\mathbf{F}$ containing sectoral physical factor usage and from a $n \times n$ direct requirements (IO) matrix $\mathbf{A}$ according to

$$\mathbf{M} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{FL}, \qquad (1)$$

where $\mathbf{I}$ is the $n \times n$ unity matrix. $\mathbf{A}$ comprises requirements from intermediate demand of domestically produced and imported commodities. $\mathbf{L}$ is used as an abbreviation for the Leontief inverse $(\mathbf{I} - \mathbf{A})^{-1}$.

The factor inventory F of a given functional unit represented by a $n \times 1$ final demand vector $\mathbf{y}$ is then simply

$$F = \mathbf{M}\,\mathbf{y}. \qquad (2)$$

$\mathbf{M}\,\mathbf{y}$ represents the indirect usage of factors embodied in all inputs into the functional unit. Further mathematical details on the IO formalism for Australia can be found in Lenzen (2001) and Wood (2009).

In this study, we are interested in decomposing the overall factor usage F into temporally and structurally important determinants, or *drivers*. We are also very interested in the role exports have to play. Hence $\mathbf{y}$ is decomposed into $\mathbf{uv}YP + \mathbf{b}Z$, where $\mathbf{u}$ is the $(n \times d)$ matrix of d categories of final demand relating individual components of final demand to absolute levels of final demand for each category ($u_{n,d} = y_{n,d}/y_d$); $\mathbf{v}$ is the vector of length d relating categories of final demand to gross national expenditure (GNE) ($v_d = y_d/Y$); Y is the per-capita measure of economic activity (GNE); and P is the population. The term $\mathbf{b}Z$ refers to exports and is hence independent of domestic population or expenditure measures. This term shows the mix of products going to export $\mathbf{b}$ and the overall level of exports Z. Thus, we are able to distinguish changing export orientation, shift to service sectors, personal affluence (expenditure per person), and population, among many other potential drivers, in their effect on the overall material metabolism of Australia over the past 30 years. Equation 2 becomes:

$$F = \mathbf{FL}(\mathbf{uv}YP + \mathbf{b}Z). \qquad (3)$$

In the IO applications of this study, we focus on handling imports and exports as flows within the environmental-economic system; hence, we embody domestic, imported, and exported material flow within the SDA calculation. We thus talk about DMI rather than pure DE or exogenously corrected consumption (DMC). Imports are modeled implicitly in the calculation (that is, if the imports are material in nature, as part of $\mathbf{F}$, and if they are immaterial in nature, as part of $\mathbf{L}$), and exports share the burden of domestic extraction and processing by linking them to $\mathbf{FL}$. We also analyze two separate representations of F, being DMI as defined above, and the total material requirement TMR, which includes unused flows.

Structural Decomposition Analysis

The basic approach to additive (see Hoekstra and van den Bergh 2003; Choi and Ang 2003; Lenzen 2006) structural decompositions of a function $y\ (x_1, x_2, \ldots, x_m)$ of m determinants is through its total differential

$$\mathrm{d}y = \frac{\partial y}{\partial x_1}\mathrm{d}x_1 + \frac{\partial y}{\partial x_2}\mathrm{d}x_2 + \ldots + \frac{\partial y}{\partial x_m}\mathrm{d}x_m. \qquad (4)$$

In this case $y\ (x_1, x_2, \ldots, x_m) = x_1 \cdot x_2 \cdot \ldots \cdot x_m$ (with the x_i being scalars, vectors or matrices),

$$\mathrm{d}y = \prod_{j=1, j\neq 1}^{m} x_j \mathrm{d}x_1 + \prod_{j=1, j\neq 2}^{m} x_j \mathrm{d}x_2 + \ldots + \prod_{j=1, j\neq m}^{m} x_j \mathrm{d}x_n = \sum_{i=1}^{m}\left(\prod_{j=1, j\neq i}^{m} x_j\ \mathrm{d}x_i\right). \qquad (5)$$

Analyzing discrete time series with a divisia decomposition approach, differences Δy are obtained by integrating infinitesimal changes $\mathrm{d}y$:

$$\Delta y = \int_{y_0}^{y_1} \mathrm{d}y = \int_{x_{1,0}}^{x_{1,1}} \prod_{j=1, j\neq 1}^{m} x_j \mathrm{d}x_1 + \int_{x_{2,0}}^{x_{2,1}} \prod_{j=1, j\neq 2}^{m} x_j \mathrm{d}x_2 + \ldots + \int_{x_{n,0}}^{x_{n,1}} \prod_{j=1, j\neq m}^{m} x_j \mathrm{d}x_m = \sum_{i=1}^{m}\left(\int_{x_{i,0}}^{x_{i,1}} \prod_{j=1, j\neq i}^{m} x_j \mathrm{d}x_i\right). \qquad (6)$$

To compute the integral one has to know what average values y assumes while the x_i change from

$x_{i,0}$ to $x_{i,1}$ (the "integral path"). Conventional parametrical divisia methods assume a parametrical average $\bar{y}^{\alpha} = y_0 + \alpha(y_2 - y_1) = y_0 + \alpha\Delta y$, with $0 \leq \alpha \leq 1$. Searching for a nonparametric method, Ang and Choi (1997) and Ang and Liu (2001) propose the logarithmic mean $\bar{y}^{\lambda} = \Delta y / \Delta(\ln y)$. The resulting logarithmic mean divisia index (LMDI) formulation

$$\Delta y^{L} = \sum_{i=1}^{n} \frac{\Delta y}{\Delta(\ln y)} \ln \frac{x_{i,1}}{x_{i,0}} \tag{7}$$

is nonparametric, exact, and time-reversible (for proofs see Ang and Choi [1997] and Ang et al. [1998]). A number of different indexing techniques have been proposed in the literature, but as there is no single "correct" method, Ang (2004) recommends the LMDI in these types of applications (for a more complete overview see Lenzen [2006], Hoekstra and Van den Bergh [2002] and Janssen et al. [2001]). Issues were found when applying the original formulation of the LMDI to IO tables (Wood and Lenzen 2006), where the high number of zero values influenced results due to the handling of the logarithmic term. Hence, when applying the LMDI formulation, limits rather than tiny values were used for the logarithmic term (see Ang and Liu 2007).

Applying equation (6) to equation (3) gives:

$$\begin{aligned}\Delta F = {} & \Delta\mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}(\mathbf{uv}YP+\mathbf{b}Z)\\ & +\mathbf{F}\Delta(\mathbf{I}-\mathbf{A})^{-1}(\mathbf{uv}YP+\mathbf{b}Z)\\ & +\mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\Delta\mathbf{uv}YP\\ & +\mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{u}\Delta\mathbf{v}YP\\ & +\mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{uv}\Delta YP\\ & +\mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{uv}Y\Delta P\\ & +\mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\Delta\mathbf{b}Z\\ & +\mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{b}\Delta Z\end{aligned} \tag{8}$$

where each factor change (for example $\Delta\mathbf{F}$) is calculated according to equation 7, not simply as, for example, $\mathbf{F}_1$-$\mathbf{F}_0$ (which is a type of conventional parametric divisa index, as per equation 6).

The terms of Equation 8 are named by their difference factor (table 1). Material intensity $\Delta\mathbf{F}$ is TMR or DMI per dollar of gross production by sector. Industrial structure $\Delta\mathbf{L}$ reflects the technological or IO relationships, and shows the total inputs by sector for a unit of final product by sector. Changes in this factor would show substitution between one production chain with another production chain. The mix of final demand $\Delta\mathbf{u}$ is the type of product per destination of final demand. Changes in this factor would show changes in the consumption habits of the populations and other types of final demand (e.g., infrastructure, and so on). Destination of final demand $\Delta\mathbf{v}$ shows the effect of changes in the amount of private and government current and capital expenditures. Affluence ΔY is the per-capita expenditure (GNE) of the population ΔP (GNE differs from gross domestic product [GDP] in that imports are included, but exports are not). Type of export $\Delta\mathbf{b}$ is the relative mix of export while overall export volume ΔZ is self-evident.

Table 1 Description of structural decomposition components

Factor	*Description* *The change in total material flow reflected in the changes in:*
$\Delta\mathbf{F}$	Material intensity
$\Delta\mathbf{L}$	Industrial structure
$\Delta\mathbf{u}$	The mix of final demand of goods and services from the industries
$\Delta\mathbf{v}$	The relative change in destination of final demand
ΔY	Affluence–the change in the per-capita GNE (gross national expenditure)
ΔP	Population
$\Delta\mathbf{b}$	The relative change in type of goods and services to export
ΔZ	Export level–the change in overall volume of exports
ΔF	Total change in material flow (summation of above terms)

Data Sources

Source for economic data ($\mathbf{L}$,$\mathbf{u}$,$\mathbf{v}$,Y,$\mathbf{b}$,Z) was the Australian Bureau of Statistics (ABS 2004, 2005a, 2006), especially publications 5209.0 and 5215.0. Eighteen sets of tables have been published by the ABS, with the years being year 1968–69, 1974–75, 1977–78, 1978–79, 1979–80, 1980–81, 1981–82, 1982–83, 1983–84, 1986–87, 1989–90, 1992–93, 1993–94, 1994–95, 1996–97, 1998–99, 2001–02, and 2004–05. Extensive reclassification and balancing was required due to changes in classification over time. Economic data were also required in constant prices. To convert the original current price tables to constant prices, we applied price indices by sector and reconciled the inflated figures with available constant price national account data. A complete description of the data-processing steps is available in a related publication (Wood 2009). Material flow data were sourced from the Australian Bureau of Agricultural and Resource Economics (ABARE), which publishes annual historical data on commodity production (Australian Bureau of Agricultural and Resource Economics 2008). These data were complemented by the United Nations' FAO database, which has more complete data for food commodities (FAO Statistics Division [FAOSTAT] 2008). Further data were available from the ABS on building approvals, dwelling size, and road construction (ABS 2008, 2005b). Finally, waste statistics were taken from state environmental reports, and the National Pollution Inventory (NPI) was used to calculate emissions to air, water, and land (National Pollutant Inventory 2008).

Data on unused flows are not readily available for Australia. The derivations applied by Poldy and Foran (1999) are used in this work. We have updated erosion coefficients from the National Land Water Audit (Lu et al. (2003), table 2). We outline this data further in the appendix available as supplementary material on the Journal's Web site.

Limitations

The limitations of this study can be summarized as:

1. Lack of detail on data on unused extraction, including comprehensive coverage of all materials by individual industry, and data on foreign trading partners.
2. Data stability of input output data; it is difficult to obtain an idea of how stable the final constant price data is and how much an effect classification changes have. This is analyzed elsewhere (Wood 2009). We minimize the effects of stochastic variation in this study by applying rolling averages to each combination of IO tables.
3. Using monetary IO tables instead of physical IO tables to analyze structural changes (Dietzenbacher 2005). As such, sectors that pay different prices for the same material will show up differently in results. Overall, the average is the same.

Results and Analysis

Total Material Flow

Since the mid-1970s, DE has grown by a factor of 2.5 while TMR has grown by a factor of almost 3.5 (figure 2). This growth, and the difference in the rates of growth, is mostly due to an expansion of the mining industries in Australia, principally due to export demand. This is reflected in the graph of DMC, which has been fairly stable since the late 1970s. Imports reflect only used flows and generally represent only about 3% to 4% of domestic material production. Exports are much more significant, with up to 60% of total domestic material production being exported. The rapid rise following the mid-1980s is due mostly to black coal exports but also to expansion of gold and diamond mining, which have low yields of final product per unit of mined ore (see figure 3). In parallel, the material flows of the agriculture sector are reducing slightly due to declines in total sheep numbers and thus less soil erosion as the international demand for wool lessens.

The evolution of the efficiency of production is shown in figure 4 for TMR. This is the estimated material flow per $ GDP. DMC is not shown as GDP includes export valuation, which is excluded in DMC. Results for DE show identical trends to TMR. The principle result from this figure is the reasonably large efficiency improvements across time. Hence, although more material is being processed, particularly for export, economically, it is being done in a more efficient manner. Two explanations are available for this—either the economy has become more material-efficient, or we are seeing inflationary effects. To separate these impacts, we also plot evolution in constant prices.

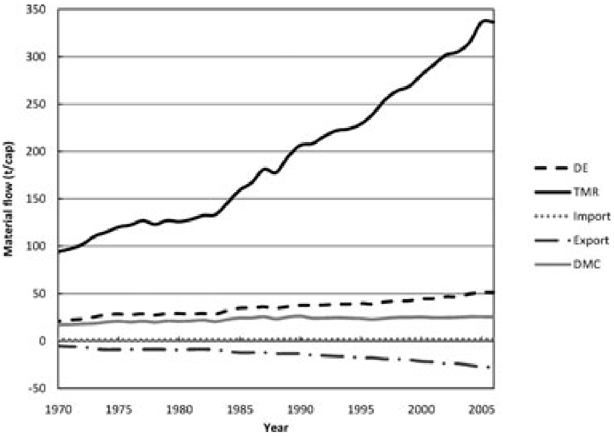

Figure 2 Per-capita material flow estimated for Australia in tonnes per capita.

Constant-price time series (figure 4) demonstrate that most intensity improvements are more to do with price increases than real efficiency measures. Farming and construction have both managed to achieve real efficiency measures, but mining intensity changes have largely occurred due to price increases. TMR of mining even increases, which is consistent with declining ore grades as reported by Mudd (2007). The most important component of these results is that of coal mining, with overburden increasing around a factor of 10 over 30 years. In fact, the overburden of the coal industry is responsible for more than 50% of Australia's TMR and is so important that changes in it overwhelm other material changes. Schandl and colleagues (2008) discuss the geographic and economic importance of some of these sectors, and we refer the reader to this work for this interpretation.

Structural Decomposition Analysis

The decomposition of these material flows according to equations 7 and 8, averaged over the time series, is presented in figure 5. As previously mentioned, results of this part of the analysis refer to domestic, imported, and exported flows endogenous to the variables shown. Although imports could be handled explicitly like exports in the presentation of results, we do not do the same due to their minor contribution to final outcomes. We present results for both TMI and DMR, as outlined in the method, to give a direct comparison between the measures.

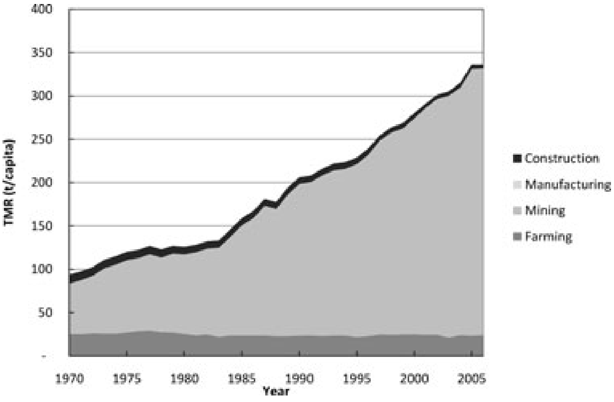

Figure 3 Components of per-capita TMR estimated for Australia in tonnes per capita (t/capita). The manufacturing component is too small to be visible.

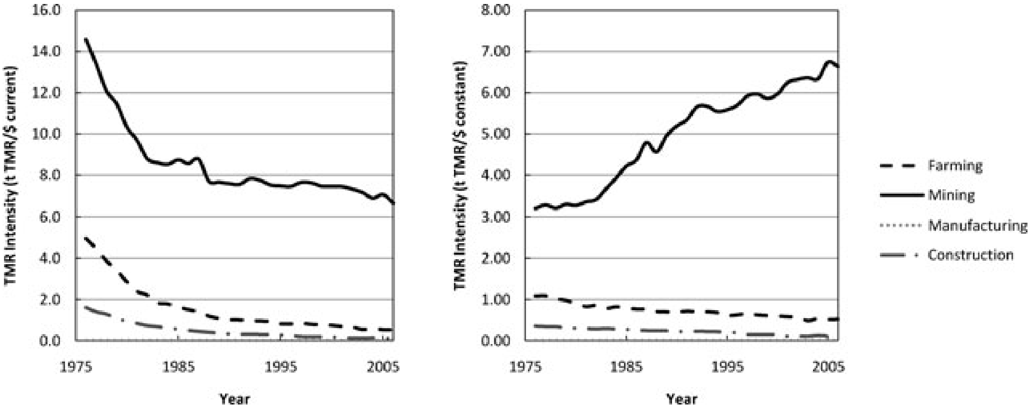

Figure 4 Evolution of TMR intensity in tonnes (t) per $ GDP for current and constant (2005) prices.

The key driver for increasing material usage of both DMI (figure 5) and TMR (figure 6) is first, not surprisingly, volume of exports ΔZ, as we have already discussed. The mix of exports $\Delta \mathbf{b}$ is also shifting to more material-intensive products; in particular, this occurs for items with high unused flows, as shown by the larger impact of $\Delta \mathbf{b}$ in TMR compared with DMI. Other effects include structural changes $\Delta \mathbf{L}$ in the economy, which shows just less than a 0.5% per annum (p.a.) shift toward more resource intensive flows. This is to say that the technology used in Australia production is becoming more reliant on material extraction—probably at the expense of labor and capital. Domestic final demand mix $\Delta \mathbf{u}$ and destination $\Delta \mathbf{v}$ show limited change in type of consumption (i.e., there has been no "greening" of consumption in Australia), as well as limited change in capital versus current consumption ($\Delta \mathbf{v}$). As expected, increases in domestic population ΔP and affluence ΔY has passed through the economy with roughly a 0.2% to 0.4% p.a. increase each.

The notion of a steady-state system where resource efficiency improvements allow improving affluence in parallel with declining resource consumption (the "factor 4" or "factor 10 "of von Weizsäcker et al. 1997) has not been observed in the Australian economy to date (see UNGASS 1997). Small improvements in efficiency have been more than offset by large economic demands.

These results show the obvious effects of export volume, population, and affluence having large aggregate effects on material input. We also know that there are some important changes occurring within our export mix $\Delta \mathbf{b}$, technological structure $\Delta \mathbf{L}$, and in material intensity $\Delta \mathbf{F}$. To

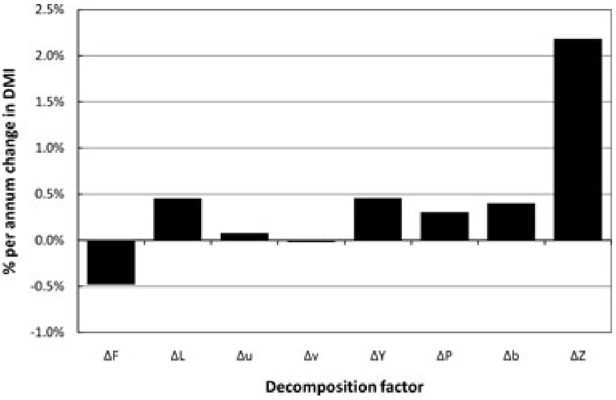

Figure 5 Average per annum affect of each determinant across the time series on direct material intensity. Values are calculated relative to average gross DMI.

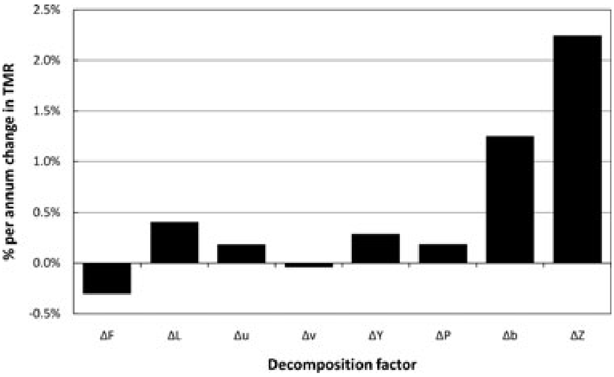

Figure 6 Average per annum affect of each determinant across the time series on total material requirements. Values are calculated relative to average gross TMR.

understand these effects further, the aggregated decomposition shown in figures 5 and 6 can be further decomposed at the level of each individual flow. We hence present results by extractive industry (that is, by the type of goods entering the economy) and by consumptive industry (that is, the type of goods and services leaving the economy). Only the major extractive industries contributing to overall change in DMI and TMR are included (a material having a greater than 1% change from average material flow for any decomposition factor).

The agricultural and mining industries become obvious as the main drivers for change. Within agriculture, there are decreases in material intensity $\Delta\mathbf{F}$ for beef cattle, offset directly by its increased use within the economy ($\Delta\mathbf{L}$). Sugar cane shows the opposite—more inputs, but less relative use. Black coal is the key material in terms of exports—with higher overall volumes ΔZ and higher relative volumes $\Delta\mathbf{b}$ compared with other types of exports. One interesting result is the fact that material intensity $\Delta\mathbf{F}$ of black coal decreased for DMI but increased for TMR. This result reflects the increasing amounts of overburden being produced in coal mining relative to ore as miners go to greater depths (Mudd 2007). The importance of other mining industries is evident in table 2, with large per annum changes in export volume ΔZ for metal ores. Improvements have generally been seen in the material intensity $\Delta\mathbf{F}$ of these industries, excluding gold, which interestingly enough has become more popular with Australian consumers ($\Delta\mathbf{u} = +0.2\%$). Comparing results from TMR and DMI, it is evident that, as would be expected, high value materials are evident in TMR, as these often have large unused flows associated with them. DMI, in contrast, has a number of low-value products such as gravel and construction materials, which embody very little unused flows. This result reinforces the importance of at least being aware of unused flows in high value products.

The decomposition by consumptive industry (table 3) shows the major categories of final consumption that have been driving change. These results show where material leaves the economic system and flows to final consumption (or export). We use "industry" rather than product as the classification of goods and services is in industrial rather than product classification, and the values hence represent the type of output from each industry. The presence of a similar range of industries in table 3 to those shown in the extractive breakdown (table 2) is further evidence that key changes have been occurring in industries with minimal processing—that is, it is the same industries that extract high volumes of material that deliver it to final demand. Little change has occurred in increasing the circulatory production of material intensive resources (by value adding) in Australia. The exceptions to this are fresh meat (in TMR) and in DMI, raw sugar, alumina (which is a processing industry of bauxite), and electricity supply; however, all of these industries are fairly minor in terms of value adding. There has been greater use of alumina products (indirectly through demand for aluminum) in the economy (shown in $\Delta\mathbf{L}$) and slightly elevated exports ΔZ of this processed product. In comparison, electricity has grown most through material intensity effects $\Delta\mathbf{F}$, which would be due to the almost

Table 2 Decomposition at the level of material type—average annual factor change by industrial output relative to total average material flow

	Extractive industry	ΔF	ΔL	Δu	Δv	ΔY	ΔP	Δb	ΔZ
TMR	Beef cattle	−0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
	Black coal	0.1%	0.1%	0.1%	0.0%	0.1%	0.0%	1.2%	1.3%
	Iron ores	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.4%
	Copper concentrates and ores	−0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%
	Gold	0.2%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
DMI	Sugar cane	0.2%	−0.2%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.1%
	Black coal	−0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.6%	0.7%
	Brown coal	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Crude oil	−0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
	Iron ores	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.8%
	Bauxite	−0.1%	0.2%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.2%
	Gravel	−0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Construction materials	−0.3%	0.1%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%

Note: See table 1 for definition of the factor changes.

complete reliance on coal for electricity production. Note, in these results, $\Delta\mathbf{F}$ shows changes in material intensity rather than material efficiency; hence, although electricity might be using less material inputs to produce a kWh of electricity, it is actually using more material inputs per $ of constant price production.

Discussion

Although Australia's performance in some environmental sectors such as native forests and specific export fisheries can be seen as relatively good, other broader areas of environmental performance such as greenhouse gas emissions, mammal extinctions, stressed river systems, and various footprint indicators present more complex challenges for policy roundtables (Morton et al. 2009; WWF 2008). Accepting MFA as a key systems indicator for policy is thus problematic because its reduction would mean a conflict with activities that drive economic growth and international trade. At least historically, the

Table 3 Decomposition at the point of output from industry—average factor change by industrial output relative to total average material flow

	Consumptive industry	ΔF	ΔL	Δu	Δv	ΔY	ΔP	Δb	ΔZ
TMR	Black coal	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	1.2%	1.3%
	Iron ores	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.4%
	Gold	0.2%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
	Fresh meat	−0.1%	0.1%	−0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
	Copper, silver, lead, zinc	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%
DMI	Black coal	−0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.7%
	Crude oil	−0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
	Iron ores	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.8%
	Raw sugar	0.2%	−0.1%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.1%
	Alumina	−0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	−0.1%	0.2%
	Electricity supply	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Note: See table 1 for definition of the factor changes.

results of this study show nothing in the drivers of change that would allow us to think differently. Although Australia's decision makers promote environmental policies for a developed world country, the country has maintained or even accentuated environmental and resource indicators typical of resource rich and/or developing countries (Daniels 1992). Our results clearly show a minimal shift away from low-value-adding industries and that exports of raw product are still dominant.

Of course, Australia's unique geographic and demographic circumstances form part of this dilemma: A relatively small population, a large land area, and rich mineral deposits currently consign it to an industrial structure skewed towards extractive primary industries, which support other countries' material requirements, and this explains part of the lack of developed-world MFA indicators. This is demonstrated by the significant role energy and mineral exports play in Australia's material flow and the increasing role exports have been shown to play in Australia's material extraction. In Australia's case, and perhaps generally in a regional context, the general assumption that TMR is a proxy for environmental pressures does not necessarily hold. Australian extractive industries adhere to stringent environmental standards for each new development and have relatively low areal requirements (for example, compared with agriculture) so that a local mine does not necessarily mean local environmental problems (Driussi and Jansz 2006). This can be seen by the dominance of coal overburden in Australia's TMR in comparison with more polluting activities. A significant environmental legacy does exist, however, of mine developments from previous eras (see, for example, Mudd [2005]). In a global context, however, Australia's TMR does matter, because

- Australia's mineral exports are globally significant,
- its expected exports of black coal and natural gas out to 2050 could cause 56 billion tonnes[4] of carbon dioxide emissions if combusted without carbon capture and storage technologies,
- much of these exports are used in overseas production processes where TMR is a good proxy for many other environmental impacts (for example, steel making), and
- much of these exports end up embodied in consumer items that are imported back into Australia.

This means that were Australia to take environmental policy seriously, and thus promote material flow indicators to equal standing with GDP and employment growth rates, decision makers would have to adopt a more systematic viewpoint of the flows and feedbacks involved in the global materials cycle. Japan, for example, is developing industrial "sound material cycles" that aspire to give an economy with negligible inputs of virgin materials, particularly metals (Moriguchi 2007).

Were MFA implemented in a globally scoped new environmental policy framework, a daily analysis of material trends would almost certainly lead to three profound changes in national policy and action. These changes would relate to growth policies; the focus on efficiency; and the extension for the responsibility of our trade policies.

As for the first item: In most national forums, figures 5 and 6 would show the resounding success of a two-generation policy focus on population and economic growth, and the promotion of affluence in society. Were material flow data seen as environmental performance indicators, however, they would show abject policy failure. Mainly through material-intensive exports that provide for manufactured imports, changing technology, population, and affluence together have accelerated DMI and TMR by 3.9% and 4.5% per annum, respectively, while efficiency policies could only retard them by 0.3% and 0.5% per annum, respectively—an almost tenfold difference in overall long-term trends. The tensions here between economic and environmental world views and aspirations are almost insoluble in a resource-rich country so dependent on global trade. To address these material flow trends, policy would need to constrain affluence and population growth or at least the links of these factors to the primary industries. In the process this could reveal a serious deficiency in the manufacturing, utility, and service sectors expected in an advanced economy. Constraining physical affluence in a material sense would perhaps even entail fundamental societal reorientation, here and in most economies, as with few exceptions, affluence expansion has been the driving rationale for human civilization.

Second: The drive for efficiency, be it based on financial budgets or industrial processes, usually generates the rebound effect (Holm and Englund 2009; Hanley et al. 2009; Hertwich 2005; see also the link between efficiency- and affluence-driven rebounds in Alcott 2008) by decreasing price but increasing availability and finally overall volumetric throughput. Thus efficiency, the centerpiece of many government and business policies, can potentially have the perverse effect of stimulating material flow or at least reducing the value of the policies. Although our results do not prove this rebound effect, we are seeing increasing volumes accompanying the improvements in efficiency. Korhonen (2007) makes a good case for systematically implementing inefficiency as a feature in national policy to ensure that uniqueness and diversity are maintained throughout most regions and countries of the world. Illogical as this may seem, inefficiency for some sectors is enshrined in many countries in cultural (animal slaughter protocols for Islamic countries) or resilience terms (protection of high-cost agriculture in Japan). Land-use policies in the European Union reward more biological or organic forms of agriculture because of ecosystem advantages and local employment generation. A transition to low-carbon and renewable energy is inherently inefficient in narrow economic terms, as it requires higher infrastructure volumes and cost per unit of energy service, but its rewards are global, in eventual lowered atmospheric concentrations of greenhouse gasses.

Third and finally, because Australia's TMR is driven both by bulk and precious minerals, policies to decrease it would require that minerals exporters actively engage with destination countries to ensure that their products become the catalyst for lower material flows in those countries, and the product volumes themselves progressively decline. Hypothetically, iron ore could only be exported to give low-impact suburbs and rapid mass transit systems rather than as feedstock for motor cars and superfluous consumer goods. Similarly, coal and natural gas exports could contribute mainly to building renewable energy infrastructure, thus possibly requiring a more massive physical capital to ensure lower physical flows for subsequent generations. Significant potential could also exist for metals such as gold, which are mined in small quantities but represent high value, have enjoyed continued growth, and find sophisticated uses in high-tech equipment (Huleatt and Jaques 2005). Material flows from uranium mining require stringent global management at this level and similar approaches are being trialed for other environmentally sensitive metals such as lead. However, it would be a divergence from current thinking in the realm of global business if producers would engage with customers' futures to ensure that product volumes, both in origin and destination countries, actually decrease over time.

That globalization, and its attendant intercountry commodity flows, poses the biggest challenge to institutionalizing the material flows concept and has been a regular theme in the literature since the inception of MFA methodology. Giljum and colleagues (2008) note the political tension between dematerialization scenarios for Europe, and trade policies for other OECD countries such as Canada, the United States, and Australia where material extraction and basic industries are more important. Should every country move to a "more circular" lower impacting economy, then trade would virtually cease. Developing countries would be then stranded with little capacity, save aid monies, to progressively step out of currently constrained livelihoods. Weisz and colleagues (2006) come to similar conclusions in an analysis of the EU-15 where they note a number of "natural" distinctions between even adjoining countries due to resource endowment and national area per capita. Behrens and colleagues (2007) cut closest to the essential issue by highlighting that the "wealthiest regions of the world [. . .] are responsible for a disproportionate share of global resource extraction and use in relation to their population" (p. 452). Unless wealthy countries contain their desire to grow their economy and per-capita affluence, then material flows must continue to grow. In the absence of a systemic revolution in why economies exist, MFA remains an excellent way to measure the sickness of the patient, but measurement alone of course does little to change the patient's behavior and then generate a trend toward robust good health.

Conclusion

This article presents a structural decomposition analysis of the material flow in Australia for the period 1975–2005. Through the application of this method we are able to distinguish changing export orientation, material intensity, personal affluence, and population growth, among many other potential drivers, and their effects on the overall material metabolism of Australia over the past 30 years.

Between 1975–2005 Australian TMR and DMI has more than tripled. The major determinants for this change are found to be, in order of importance: export growth; affluence growth; increasing material flows within economic structure; and population. Only material intensity was seen to have a significant retarding effect on material flow. Other structural components had small effects at the aggregate level.

At a more detailed level, however, the importance of the energy and mineral sectors in extracting mineral resources is apparent. Improvements in mining techniques have reduced material requirements, but increased exports and consumption within the economy has offset these reductions. From a consumption perspective, energy and minerals are still important as well as some manufacturing production. No major impacts occur from changing demand in service sectors. The lack of any significant shift in the Australian economy from minimally processed export goods to manufacturing and service production could be seen as a failure in moving toward a knowledge-based society.

The full rollout through Australian society and business of material flow accounting and a systematic response to its implications, will require a change in the national growth focus of the last two human generations, the re-embrace of inefficiency in particular economic sectors, and the reversal of neoliberal and globalized trade policies that have dominated the globe for the past decades. Because it poses such visceral challenges to global economic values, it is perhaps unlikely that MFA will be institutionalized in national policy making quickly. In the interim, it would be good if greater emphasis is placed on improving the role of MFA in Australia.

Notes

1. A body of work has been published, with a publication accessible in English by Moll and colleagues (1998).
2. ConAccount began in May 1996 as a concerted action supported by the European Union (EU) titled "Coordination of Regional and National Material Flow Accounting for Environmental Sustainability". www.conaccount.net/. It continued after EU funding ended and is a chapter within the International Society for Industrial Ecology.
3. We find it hard to reconcile the fact that uneconomic flows of mining, forestry, and other agriculture (tailings, wood offcuts, and so on) are not counted in domestic extraction for livestock, yet natural growth of grasses must be counted as a material/economic input to livestock production. The argument for excluding plants in other sectors is stated as (Weisz et al. 2007, 10):

   > *"Statisticians would be forced to convert rather robust and valid data on annual agricultural and timber harvest to comparable weak estimates of the primary inputs needed to produce these plants. Moreover, all differentiation between different types of crops would be lost, as well as the conceptual link to the system of national accounts. It is hard to imagine how such data could possibly be interpreted in any meaningful way, given the limitations of a black box accounting system such as MFA."*

   We do not see how this can be interpreted any differently to natural growth of rangelands for livestock production. By calculating grazed biomass rather than animal weight, we are making an inconsistency with national accounts boundaries, we are placing weak assumptions on uptake of dry matter from very different grazing lands, and we are losing the differentiation in the type of livestock (we would see grazed biomass rather than sheep or cattle).
4. One (metric) tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons. All tonnes in this article are metric.

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Supplementary Material

Additional Supplementary Material may be found in the online version of this article:

Supplement S1. This supplement contains an appendix with additional information on the calculations and data used to estimate the total material requirement (TMR) for Australia.