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Australia's consumption-based greenhouse gas emissions*

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We use data from the World Input-Output Database in a multiregional input–output model to analyse Australian consumption-based greenhouse gas emissions for the years 1995 to 2009. We find that the emission content of Australian macroeconomic activity has changed over the 15-year period. Consumption-based emissions have been growing faster than production-based emissions since 2001. We show that emissions embodied in Australian imports are increasingly becoming a significant source of emissions. We investigate emissions in Australian imports and find that increased trade with China contributed substantially to the increase in Australia's consumption emissions. China was the largest exporter of emissions to Australia and accounted for almost half of emissions embodied in Australian imports since 2002. The growth of trade with China coincides with the increase in imported emissions as well as the increase in aggregate consumption emissions. Our results suggest that tracking consumption emissions together with production emissions provides a more complete picture of Australian emissions.

Key words: consumption emissions, greenhouse gases, international trade, production emissions.

1. Introduction

It is generally understood that greenhouse gases (GHG) produced by human activities are having a warming effect on the climate (IPCC, 2014). Concerns for the harmful effects of a warmer climate have made reducing GHG emissions a priority on political agendas around the world. However, climate change is a global externality, and policies or agreements that have been implemented to reduce emissions are incomplete in the sense that a large set of GHG producers are not included in them.

Emissions embodied in international trade are important when agreements are incomplete because they can distort a country's measure of its GHG emissions (see Wyckoff and Roop (1994)). Measures of emissions might be artificially low if a country is importing goods with significant GHG content.

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Because of the distorting effect that trade can have on emissions accounting, studies have computed the GHG content of international trade. Davis and Caldeira (2010) calculated that 23 per cent of global CO₂ emissions were traded internationally in 2004. Moreover, there is evidence that trade in emissions is increasing: Peters *et al.* (2011) find that emissions embodied in international trade increased from 20 per cent in 1990 to 26 per cent in 2008. Importantly, they find that the net transfer of emissions from the developing world to developed countries increased by almost 300 per cent.

The growth of GHGs in international trade and the need to better understand linkages between economic activity and emissions has motivated research into how to account for GHG emissions (see Munksgaard and Pedersen (2001) and Peters (2008)). There are two methodologically distinct accounting principles: production-based emissions and consumption-based emissions (see Lenzen *et al.* (2007) for a third option that combines the two). Production-based emissions are those that arise from domestic production of goods and services including those exported to foreign markets. Emissions targets in national and international climate programs are usually a variant of production-based emissions. The Kyoto Protocol requires signatory countries to report territorial emissions, which are essentially production emissions. Consequently, national policies and international agreements target domestically produced emissions and ignore imported emissions.

Consumption-based measures of emissions attribute GHG emissions from the production of goods and services to final use (see Munksgaard and Pedersen (2001), Peters (2008), Wilting and Vringer (2009) and Barrett *et al.* (2013)). The key difference between production-based and consumption-based emissions is in the accounting of emissions embodied in international trade. Consumption-based emissions account for emissions embodied in imports including trade in intermediate goods. The implication is that more emissions are covered in the presence of limited participation in agreements. Expanding coverage to emissions imported from nonparticipating countries has the potential to reduce the likelihood of emission leakage from participating countries to nonparticipating countries. There is a concern that declining production emissions experienced by some manufacturing sectors in developed countries (or the decrease in the growth of production emissions) are being achieved through the outsourcing of emissions to developing countries like China (see Levinson (2010) and Aichele and Felbermayr (2015)). Tracking both production and consumption emissions can help policymakers identify potential concerns with outsourcing GHG emissions.

The endogenous relationship between GHG policy and international trade implies that policies directed at kerbing emissions are best evaluated if all emissions from economic activity are accounted for. Informed policy evaluation requires a good understanding of any changes that may have occurred to emissions over time including changes in the sources of emissions across economic activity and between countries. Policymakers monitoring only production emissions could overestimate the effectiveness of GHG

mitigation policies because of the potential for domestically produced emissions to be substituted with imported emissions. Analysing consumption emissions jointly with production emissions ensures that GHG policies, which have economic costs, are not redistributing emissions across regions or economic activities, but actually reducing them. Even if a country's production and consumption emissions are roughly similar, it is still important to track both emissions because they are linked to different macroeconomic activities and policymakers can identify any redistribution of emissions. A few countries have considered reporting consumption emissions as part of their official statistics; the United Kingdom is one example (see Barrett *et al.* (2013)).

The objective of this paper was to contribute to the economics of Australia's GHG emissions by investigating linkages between Australian macroeconomic activity and emissions. We provide a joint analysis of Australia's consumption and production emissions between 1995 and 2009 using a global input–output model and data from the World Input-Output Database (WIOD). We compare Australian production emissions to consumption emissions. The two measures of emissions have followed different trajectories suggesting that the emissions associated with different macroeconomic activity have changed over time.

Our second contribution is our analysis of the contributing factors underlying the observed changes in GHG emissions. We compute various emission intensity ratios and track how these have changed over time. The WIOD has a unique feature: the tables are reported in current-year prices as well as in previous-year prices. We construct a price deflator directly from the data in the WIOD at the country-sector level that we use to control for changes in prices when we compute various emission intensity measures. We show that the emissions embodied in Australian imports have increased and have become more emission intensive. In contrast, exports have become less emission intensive. We also show that the emission intensity of Australian consumption of domestically produced goods has been increasing. Third, we document the effect that increasing trade with China has had on Australian emissions. We also show how the global financial crises affected Australian emissions.

The research in this paper is related to three previous studies on Australian GHG emissions. In an important first study of Australian emission, which was reported in a series of two papers, Common and Salma (1992a,b), CO₂ emissions due to fossil fuel consumption were calculated using Australian input–output tables as well as data on fuel use in 27 Australian sectors. The present study differs from these two papers in two ways. First, we include the three main GHGs in our measure of consumption emissions: CO₂, CH₄ and N₂O. Second, we use a global input–output model to compute consumption-based emission. The global input–output methodology is an improvement over the previous papers because it explicitly accounts for emissions embodied in international trade, including internationally traded

intermediate goods, and accounts for variation in emission factors between sectors and across countries.

In a related study, Wood (2009) used input–output analysis to decompose changes to Australia’s production emissions for the years 1976 to 2005. Our work differs from Wood (2009) because we are interested in analysing the changes that have occurred to Australia’s consumption emissions and production emissions.

In another important study, Lenzen (1998) tackled the issue of computing emissions attributed to consumption by Australians by disentangling emissions in imports and exports. However, Lenzen (1998) was required to assume that emission factors of foreign production were identical to Australian emission factors and was restricted to analysing bilateral trade. We do not make the same assumptions nor are we restricted to studying emissions in bilateral trade. The global input–output model accounts for emissions embodied in intermediate goods along entire international production chains and employs sector- and country-specific emission factors.

There are two other ways in which our study differs from Common and Salma (1992a,b) and from Lenzen (1998). First, we can examine changes that have occurred in emissions over a relatively long period of time because we calculate consumption emissions for the years 1995–2009. Second, we compute various time series of emission intensities while controlling for changes in prices at the sector level in each country.

2. Methods

Computing Australia’s consumption-based GHG emissions requires accounting for all of the GHGs emitted during the production of goods and services, which are consumed in Australia. Our task is the exhaustive allocation of GHG emissions across global production chains for final goods and services consumed in Australia. Measuring the emissions associated with consuming good y requires tracking all the GHGs emitted during each stage of its production, which is complicated because the intermediate inputs used to produce good y could have come from different countries. Moreover, the intermediate inputs could have been produced using goods imported from other countries. Computing emissions in the flow of intermediate goods requires assigning the appropriate emission factors at each stage in the production chain: if intermediate input x was used to produce good y and input x used additional inputs from sectors in countries A and F , then the emission intensities from those sectors in countries A and F must be used to compute emissions caused by consuming good y .

There is a methodology for decomposing trade into trade involving intermediate goods and final consumption: global input–output analysis (see Wiedmann *et al.* (2007), Wiedmann (2009) and Peters (2008)). Rather than provide another general description of input–output analysis, we proceed with explaining the analysis using an example. There are two reasons for proceeding

with an example: First, the example clearly illustrates how emissions can be tracked over global production chains, and second, the example makes clear the mapping between the variables in the input–output model and data.

2.1 Global input–output analysis

We begin with a simple example. Assume that Australia, which we denote by A , only trades with one other country, denoted by F , and each country consists of only two industrial sectors (1, 2), with each sector producing only one good. The output from each sector, in each country, can be used as inputs into the production of the other good or for final consumption. To compute consumption emissions, we must track emissions in the flow of trade between the two countries and between sectors over the entire production path of both goods.

Let $X_{1,2}^{AF}$ denote the amount of sector 1's output, located in Australia, that is used as an input for sector 2 located in country F ($X_{2,1}^{FA}$ is similarly defined). Next, let Y_1^{AF} denote the amount of industry 1's output, located in Australia, that is used for final consumption in country F (Y_2^{FA} is similarly defined). Define total output produced by sector 1 in Australia by Z_1^A . These data can be organised in an input–output table:

	A Sector 1	A Sector 2	F Sector 1	F Sector 2	$C^A+I^A+G^A$	$C^F+I^F+G^F$	Total
A Sector 1	X_{11}^{AA}	X_{12}^{AA}	X_{11}^{AF}	X_{12}^{AF}	Y_1^{AA}	Y_1^{AF}	Z_1^A
A Sector 2	X_{21}^{AA}	X_{22}^{AA}	X_{21}^{AF}	X_{22}^{AF}	Y_2^{AA}	Y_2^{AF}	Z_2^A
F Sector 1	X_{11}^{FA}	X_{12}^{FA}	X_{11}^{FF}	X_{12}^{FF}	Y_1^{FA}	Y_1^{FF}	Z_1^F
F Sector 2	X_{21}^{FA}	X_{22}^{FA}	X_{21}^{FF}	X_{22}^{FF}	Y_2^{FA}	Y_2^{FF}	Z_2^F

The table describes the flow of goods and services into the different sectors located in each country. For example, the first row describes the flow of goods produced in sector 1 in Australia: X_{11}^{AA} is the amount of the good produced in sector 1 that is used again by Australia's sector 1, whereas X_{12}^{AF} is the amount of the good produced in sector 1, located in Australia, that is used in sector 2, located in country F .

We track the emissions in the international trade by decomposing aggregate output of each sector, in each country, into final consumption goods and intermediate goods by first constructing an input–output matrix from the input–output tables:

$$\begin{bmatrix} Z_1^A \\ Z_2^A \\ Z_1^F \\ Z_2^F \end{bmatrix} = \begin{bmatrix} Y_1^{AA} + Y_1^{AF} \\ Y_2^{AA} + Y_2^{AF} \\ Y_1^{FA} + Y_1^{FF} \\ Y_2^{FA} + Y_2^{FF} \end{bmatrix} + \begin{bmatrix} a_{11}^{AA} & a_{12}^{AA} & a_{11}^{AF} & a_{12}^{AF} \\ a_{21}^{AA} & a_{22}^{AA} & a_{21}^{AF} & a_{22}^{AF} \\ a_{11}^{FF} & a_{12}^{FF} & a_{11}^{FA} & a_{12}^{FA} \\ a_{21}^{FF} & a_{22}^{FF} & a_{21}^{FA} & a_{22}^{FA} \end{bmatrix} \times \begin{bmatrix} Z_1^A \\ Z_2^A \\ Z_1^F \\ Z_2^F \end{bmatrix} \quad (1)$$

where $a_{12}^{AF} = \frac{X_{12}^{AF}}{Z_1^A}$ is the share of industry 1's aggregate output, located in Australia, that is consumed by industry 2 located in country F . Equivalently,

a_{12}^{AF} is the input required from Australia's industry 1 by industry 2 located in country F to produce one unit of output. We simplify the analysis by writing the system of equations in (1) in matrix form:

$$\mathbf{z} = \mathbf{y} + \mathbf{A}\mathbf{z} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \quad (2)$$

where \mathbf{I} is a (4×4) identity matrix, and each element in the vector $\mathbf{A}\mathbf{z}$ gives the aggregate amount of intermediate inputs flowing between sectors in both countries. Now, if we knew the emissions associated with each input, we could calculate the total emissions requirement for final demand.

Let e_1^A denote the emission rate for sector 1 located in Australia. Similarly, e_2^F denotes the emission rate of sector 2 located in country F . These rates report the emissions generated from producing one unit of the good in each sector. We collect the emissions rates for each industry located in the two countries into the vector \mathbf{e} :

$$\mathbf{e}' = [e_1^A e_2^A e_1^F e_2^F]. \quad (3)$$

Aggregate emissions are as follows:

$$E = \mathbf{e}'(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}. \quad (4)$$

Equation (4) decomposes total emissions into those necessary to produce the goods and services to meet final consumption in both countries. Importantly, the emissions factors are country and sector specific: If industry 1, located in country F , uses intermediate inputs produced by industry 2, located in country F , then the emission factor used to determine consumption emissions is e_2^F . Appropriate emission factors are used for internationally traded intermediate goods.

One way to think about the term $\mathbf{e}'(\mathbf{I} - \mathbf{A})^{-1}$ is that it gives a new vector of emission factors that have been adjusted to account for the intermediate goods used in the production of final goods. The emissions embodied in exports must not be included in a measure of consumption emissions: Let $\tilde{\mathbf{y}}$ define final domestic demand,

$$\tilde{\mathbf{y}}' = [Y_1^{AA} Y_2^{AA} Y_1^{FA} Y_2^{FA}] \quad (5)$$

Equation (6) illustrates how emission rates are adjusted by the flow of intermediate goods when applied to final goods consumption,

$$E_C^A = \mathbf{e}'(\mathbf{I} - \mathbf{A})^{-1}\tilde{\mathbf{y}}, \quad (6)$$

and is the equation we use to compute Australia's consumption-based emissions.

3. Data

The data we used to compute consumption emissions come from the World Input-Output Database (WIOD). The WIOD consists of linked input–output tables based on a set of common industry classifications and definitions covering 40 countries and a residual country called rest of the world (RoW). In addition, the data cover 35 sectors (see Dietzenbacher *et al.* (2013) and Timmer *et al.* (2015)). These data have been used in a number of recent studies including Timmer *et al.* (2014) and Koopman *et al.* (2014).

Calculating the emissions in Australian trade requires a consistent set of trade data covering Australia's trading partners. The countries covered in the WIOD are reported in Table 1 together with their share of Australian trade in goods. The countries accounted for between 64 and 80 per cent of total Australian exports and imports between 1995 and 2009. There are some omissions including New Zealand that accounted for about five per cent of imports between 1995 and 2005 as well as Malaysia and Thailand that accounted for around three per cent of imports. The remainder of Australian trade not included in the WIOD is made up of very small contributions by different countries.

The most significant change in Australian trade between 1995 and 2009 occurred in trade with China. The share of imports coming from China increased from <5 per cent to over 20 per cent, making China the largest exporter to Australia. Australian exports to China also increased from <5 per cent to 21 per cent. The increase in trade with China raises the question: What has been the effect of the increase in imports from China on Australian consumption emissions? There is also a more subtle point; it is clear that trade with China has increased and this will affect emissions, but direct trade is not the only source of emissions. If other countries began importing more intermediate goods from China, and then shipped the final goods to

Table 1 WIOD countries and trade shares (%)

Country	1995		2009	
	Imports	Exports	Imports	Exports
Japan	20.70	23.11	15.89	19.46
China	4.62	4.36	20.59	21.63
South Korea	6.59	8.45	6.41	7.96
United States	11.75	6.45	7.20	4.88
Taiwan	4.18	4.60	2.75	3.31
India	1.25	1.53	5.28	7.36
Indonesia	2.79	3.34	2.16	2.11
Canada	1.76	1.69	0.79	0.72
Brazil	0.52	0.46	0.42	0.47
Mexico	0.14	0.11	0.49	0.42
Turkey	0.29	0.39	0.18	0.15
Russia	0.15	0.20	0.26	0.30
European Union	15.52	10.68	12.55	8.85

Australia, then the emissions from the intermediate goods from China will also be included in Australian consumption emissions.

The data in the WIOD cover 35 sectors in each country. The sectors include agriculture, mining, construction, utilities, 14 manufacturing industries and 17 service industries (a complete list of sectors is provided in the Appendix S1). It should be noted that even though there are 35 sectors in the WIOD, these have been aggregated from more disaggregated sector data. This assumption has the potential to introduce aggregation errors because each sector aggregated into a parent sector is assumed to have the same emission factor. Using the data in the WIOD for each of these 35 industries and 40 countries, we construct matrix A in equation (6), which is now a 1400×1400 matrix with each element equalling

$$a_{ij}^{rp} = \frac{X_{ij}^{rp}}{Z_i^r} \quad (7)$$

where $r, p = 1 \dots 40$ indexes the flow of goods from country r to country p and $i, j = 1 \dots 35$ indexes the flow of goods into the different sectors. Final demand for the goods produced in each sector in each country, Z_i^r , is also reported in the WIOD. So, \mathbf{z} , which contains each Z_i^r , is a 1400×1 column vector. The last remaining component of equation (4) is \mathbf{y} that contains the final consumption of the goods produced by each sector. There are 35 sectors in 40 countries, so each element of \mathbf{y} is the sum

$$\sum_{p=1}^{40} Y_i^{rp}. \quad (8)$$

The WIOD also maintains an environmental database consisting of energy and air emission accounts which report the amount of CO_2 , CH_4 and N_2O emitted into the atmosphere by each of the 35 sectors in each of the 40 countries. The air emission accounts in the WIOD were constructed using technology-specific emissions factors obtained from various energy accounts and technical documents; details of the emission factors can be obtained from Dietzenbacher *et al.* (2013).

To compute an aggregate measure of GHG emissions, we converted CH_4 and N_2O into CO_2 equivalents (CO_{2e}) using the conversion factors derived from the global warming potential (GWP) index. The GWP index is the amount of warming a gas causes over a period of time (typically 100 years); the CO_{2e} of a GHG is the amount of CO_2 that has the same global warming impact as the emitted GHG. The GWP for CH_4 is 25, and for N_2O , the index is 298. The total CO_{2e} emitted by each industry in each country is G_i^r , so emission rates are

$$e_i^r = \frac{G_i^r}{Z_i^r} \quad (9)$$

where the units are tonnes per dollar and \mathbf{e} is a 1400×1 vector.

The data in the WIOD are reported in both current-year and previous-year prices. This unique feature means that a price index can be constructed to control for changes in prices, which is important for computing emission intensities over the 15-year period. Tracking year-to-year changes in intensities requires controlling for changes in prices to ensure we track changes in emissions and not changes in relative prices. Suppose that Japan exported the same amount of goods to Australia in 1995 and 1996 as well as emitted the same amount of GHGs in those years. The emission intensity of Australian imports from Japan has not changed. However, if prices increased over this period, then using values in current prices will result in decreasing emission intensities when they should be unchanged.

For each sector in each country, we use a standard chaining method applied to a Paasche-type index to calculate year-to-year changes in prices. Consider a sector located in Japan: The index for the price change between 1995 and 1996 is computed by first taking the ratio of the 1996 output in 1996 prices to 1996 output in 1995 prices. Next, we construct the same index for the price change between 1996 and 1997: The ratio of the 1997 output in 1997 prices to 1997 output in 1996 prices. The 1996 ratio is multiplied by the equivalent ratio for 1996. We have now computed an index of how prices have changed since 1995, which we can use to control for changes in prices at the country and sector level.

The amount and type of data required to compute consumption emissions relative to production emissions means that there is more uncertainty in measures of consumption emissions. The uncertainty is largely associated with the need to harmonise large data sets across the different countries. Country-specific data can differ in their currencies, levels of disaggregation of the data, sector classifications and inflation. Fortunately, some of these errors (not all) associated with the harmonisation of the data are reduced by using the WIOD tables. Recall also that aggregating sectors into 35 parent sectors can introduce some error. However, evidence suggests that there is only a small increase in uncertainty (see Barrett *et al.* (2013)).

4. Results

4.1. Consumption emissions

Australia's consumption-based emissions are illustrated in Figure 1 and reported in Table 2. Panel 1(a) illustrates emission levels and panel 1(b) reports annual growth. The dominant GHG was CO₂ which contributed, on average, 76 per cent of total consumption-based GHG emissions. The next largest GHG was CH₄, which contributed about 20 per cent of aggregate emissions. The remaining four per cent was contributed by N₂O. The annual average amount of GHGs emitted into the atmosphere was approximately 481 million tonnes (CO_{2e}).

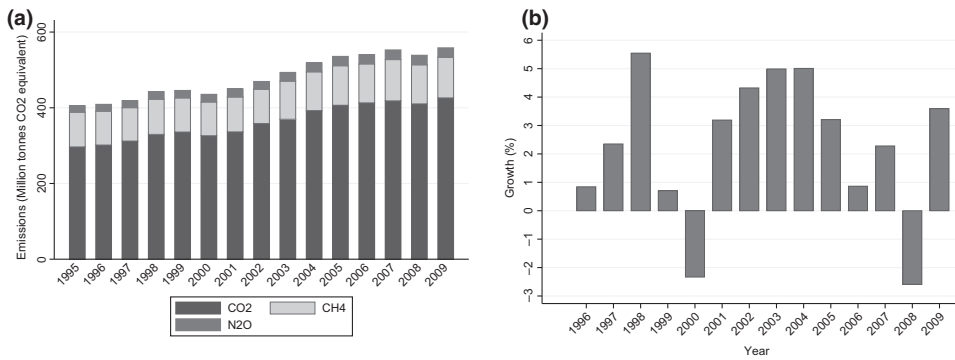


Figure 1 Consumption GHG emissions, 1995–2009.

Consumption emissions have been increasing since at least 1995. Emissions were just over 405 million tonnes in 1995. In 15 years, emissions rose to 558 million tonnes, a 38 per cent increase. There were only two years, 2000 and 2008, when consumption emissions did not grow. These were periods of economic slowdown. The negative growth observed in 2008 is consistent with the global economic impacts of the financial crises. The period with the largest persistent growth of emissions was between 2001 and 2005 with annual growth rates ranging between three and five per cent.

Consumption emissions include emissions that were emitted abroad from producing goods or services that were eventually consumed in Australia. Consequently, the increase in the growth rate of consumption emissions was not solely due to changes in Australian industrial emissions. The emissions in foreign-produced goods imported into Australia also matter.

4.2. Consumption emissions and kyoto emissions accounting

Under the Kyoto Protocol to the 1992 United Nations Framework Convention on Climate Change, Australia was required to limit its average annual GHG emissions between 2008 and 2012 to 108 per cent of its emissions in 1990. Although the emissions reported under the Kyoto Protocol are territorial emissions, they are essentially computed as production-based emissions. In Figure 2, we compare Australian production and consumption emissions. Production emissions were obtained from the Australian National GHG Inventory and include emissions from the energy sector, industrial processes, agriculture and waste. To make the comparison between consumption emissions and production emissions more precise, we did not include emissions from changes in land use or land-use change (LULUCF) because the WIOD does not include these data. However, we did compare consumption emissions to a measure of production emissions that included emissions from LULUCF. The results are similar to those reported in Figure 2. Consumption emissions surpassed production emissions in 2004.

Table 2 Consumption-based GHG emissions (Million CO₂e)

Year	Private				Government				Investment				Total
	CO ₂	N ₂ O	CH ₄	Subtotal	CO ₂	N ₂ O	CH ₄	Subtotal	CO ₂	N ₂ O	CH ₄	Subtotal	
1995	195.37	13.89	71.30	280.56	29.55	1.21	8.80	39.57	71.73	2.20	11.55	85.51	405.64
1996	199.30	14.41	69.66	283.38	29.02	1.25	8.15	38.42	73.19	2.40	11.69	87.28	409.08
1997	205.74	14.11	65.55	285.40	29.97	1.33	8.25	39.55	76.30	3.07	14.49	93.86	418.80
1998	218.65	15.22	67.93	301.79	31.98	1.43	8.36	41.77	79.11	3.53	16.49	99.12	442.68
1999	224.28	14.94	65.90	305.12	31.99	1.34	8.30	41.63	79.63	3.45	15.99	99.06	445.81
2000	222.32	15.68	66.66	304.66	32.81	1.42	8.31	42.53	71.09	3.22	14.03	88.34	435.53
2001	228.20	16.29	68.73	313.22	32.71	1.43	8.32	42.46	75.48	3.44	15.06	93.97	449.65
2002	241.60	15.67	66.34	323.60	34.52	1.42	8.29	44.24	82.41	3.50	15.76	101.67	469.51
2003	244.63	16.85	70.54	332.03	35.19	1.52	8.33	45.03	89.83	4.81	21.83	116.47	493.53
2004	257.16	17.83	73.52	348.51	37.18	1.49	8.22	46.89	98.29	4.56	20.62	123.47	518.88
2005	260.54	18.33	74.81	353.68	38.92	1.56	8.00	48.48	107.16	4.83	21.63	133.62	535.78
2006	260.74	17.87	72.16	350.77	39.90	1.52	7.83	49.25	112.35	5.11	22.94	140.40	540.43
2007	260.02	18.38	74.91	353.31	39.62	1.58	8.36	49.56	118.65	5.61	25.77	150.03	552.89
2008	259.37	18.59	73.91	351.88	42.76	1.80	9.15	53.71	108.18	4.78	20.20	133.16	538.75
2009	276.43	18.83	76.94	372.20	46.22	1.88	9.85	57.94	103.42	4.36	20.54	128.32	558.46

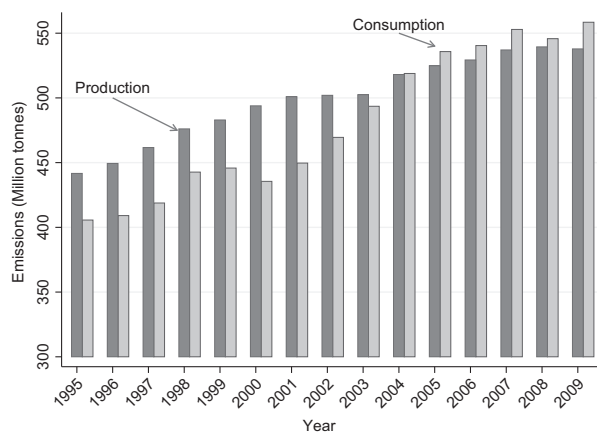


Figure 2 Consumption and production emissions.

The magnitude of the difference between production emissions and consumption emissions prior to 2002 was larger.

The comparison illustrates the almost opposite growth trajectories followed by the two measures. Production emissions were initially growing faster than consumption emissions. Beginning around 2000, there was a substantial increase in the growth rate of consumption emissions while the growth of production emissions slowed. These contrasting growth rates eventually led to consumption emissions surpassing production emissions. Prior to 2002, the average annual growth rate of production emissions was just under 3 per cent, while the average growth rate of consumption emissions was 1.8 per cent. Consumption emissions grew faster than production emissions after 2001. Consumption emissions grew, on average, 4.5 per cent each year between 2001 and 2005, while the growth rate for production emissions was <1 per cent. Consumption emissions continued to grow faster than production emissions.

There was a one-year decline in consumption emissions in 2008, which was likely due to slowdown in global economic activity caused by the financial crises. Production emissions also dropped in 2009; however, the reduction in production emissions was short-lived. Production emissions in 2010, 2011 and 2012 were all higher than the 2009 level. Production emissions in 2012 were higher than the 2008 emission levels the year prior to the one-year drop in emissions (see the Australian Greenhouse Emissions Information System [AGEIS]).

It is clear that production and consumption emissions followed different trajectories. The most significant period of change occurred between 2001 and 2006 suggesting that there was a change in the emissions associated with different macroeconomic activity. Explaining the changes in the emission content of Australian economic activity that occurred during this period contributes to understanding the linkages between economic activity and emissions.

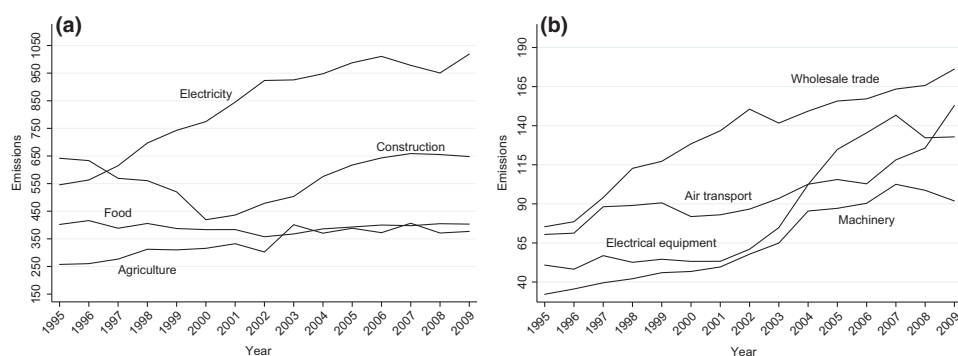


Figure 3 Sector Emissions (100,000 Tonnes CO₂e).

4.3. Emissions and economic activity

4.3.1. Emissions from intermediate consumption

Our consumption measure of GHG emissions accounts for the emissions associated with intermediate goods across the 35 sectors in 40 countries even if the goods are traded between two foreign countries. We report the emission levels for the four sectors that contributed the largest amount to Australia's consumption-based GHG in Figure 3. Emission levels for all 35 sectors over 15 years are reported in the Appendix S1. The four largest contributing sectors were (1) electricity, gas and water supply; (2) construction; (3) food, beverages and tobacco; and (4) agriculture, forestry and fishing. The electricity sector was the largest emitter with annual emissions ranging from 56 million tonnes CO₂e to 101.8 million tonnes of CO₂e and accounted for over 18 per cent of emissions. Moreover, the emissions from this sector increased by 80 per cent over the 15 years. Emissions from the construction sector were initially declining; however, emissions started to increase in 2000 so that by the end of the period, emissions were back to 1995 levels. Emissions from the food sector were essentially unchanged over the 15 years, and emissions from agriculture increased by about 45 per cent.

The average percentage change in emissions between 1995 and 2009 across all the different sectors was approximately 50 per cent. There were only two sectors that experienced a significant reduction in emissions: water transport and other nonmetallic minerals. The sectors with the largest increase in emissions were (1) electrical and optical equipment (175% increase); (2) heavy machinery (158% increase); air transport (114% increase); and (4) wholesale trade (124% increase). The emissions from these sectors are reported in panel 3(b). The figure shows that there were substantial increases in the growth rates of emissions between 2001 and 2007. These observations suggest that an important change occurred around 2001 and 2002, which affected emissions. In section 4.3.2, we show that the large increase in emissions from the electrical and optical sector can be largely explained by a substantial increase in imports from this sector in China.

Focusing just on levels can mask the fact that sectors differ in size as well as in the emission intensity of their production. A sector may be contributing a large proportion of aggregate emissions not because it is particularly GHG intensive, but because it is a large sector. We calculated an emission intensity ratio for each sector defined as the ratio of emissions to the aggregate value of consumption in each sector controlling for changes in prices. The average annual ratio across all sectors is illustrated in Figure 4 (a full set of results are reported in the Appendix S1). Average intensities were declining up to 2000 when average intensities started to increase. The timing of the increase is consistent with the increase in the growth rate of consumption emissions as well as with the increase in sector emissions. In general, the sectors with the highest intensity ratios were those reported in Figure 3. These observations suggest that an important change occurred around 2001 and 2002, which affected Australia’s consumption emissions.

4.3.2 *International trade*

We investigate the link between Australia’s international trade and emissions and show that there were significant changes in the emission content of Australian trade, which helps explain the growing difference between production and consumption emissions. In particular, there has been a substantial increase in the amount of emissions embodied in Australian imports since at least 2001.

We report imported emissions in Figure 5(a). There was little change in imported emissions between 1995 and 2001. There was a one-year increase in imported emissions observed in 1997; however, this spike was essentially erased by 2001. There was a substantial increase in imported emissions after 2001. Imported emissions grew by over 90 per cent between 2002 and 2007, which is consistent with the period of growth in consumption emissions reported in Figure 1.

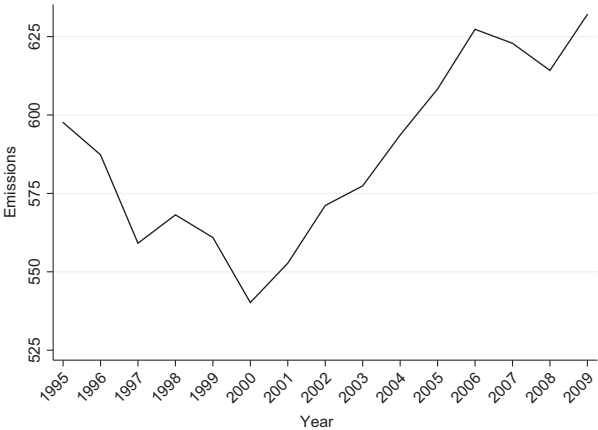


Figure 4 Emission-sector intensity ratio (Tonne/Million AU\$, fixed prices).

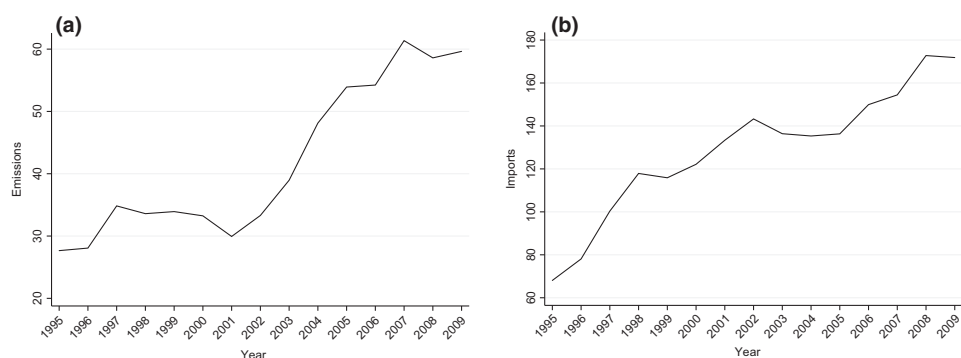


Figure 5 Goods trade and imported emissions.

There are two reasons why emissions in imports can change: first, the volume of imported goods and services can increase; second, the composition of sectors and countries producing the imported goods can change. We investigate each of these factors and show that shifts in the origin of Australian imports are an important factor in explaining the sharp increase in imported emissions.

We report Australian imports from the 39 countries included in the WIOD in the second panel of Figure 5. Values were converted to Australian dollars using exchange rates obtained from the World Bank's Global Economic Monitor (GEM) database, and nominal values were deflated using the price index constructed from the WIOD. One reason for the increase in emissions in Australian imports observed after 2001 was the growth in imports. The only period in which imports did not grow was between 2003 and 2005. Prior to 2003, imports grew by about 68 per cent, whereas after 2005, imports grew by 35 per cent.

Imports grew between 1995 and 2001, while imported emissions did not change. This observation suggests that changes in the quantity of imports are not a sufficient predictor of changes in imported emissions. Changes in sectors or countries from which the imports originate influence emissions because production is more emission intensive in some countries. One reason for the increase in emissions embodied in imports observed after 2002 was shifts in the origins of Australian imports.

We would like to know from which countries did Australia import and whether changes in the mix of exporting countries can explain the increase in emissions observed after 2002. We illustrate imported emissions from the largest contributing countries in Figure 6. A complete listing of imported emissions by exporting countries is reported in the Appendix S1. In panel 6(a) are reported the emissions from the five largest origin countries for emissions embodied in Australian imports after China. China was the largest exporter of emissions to Australia; other important exporters include the United States, Japan, Great Britain, Germany and India. The second panel reports

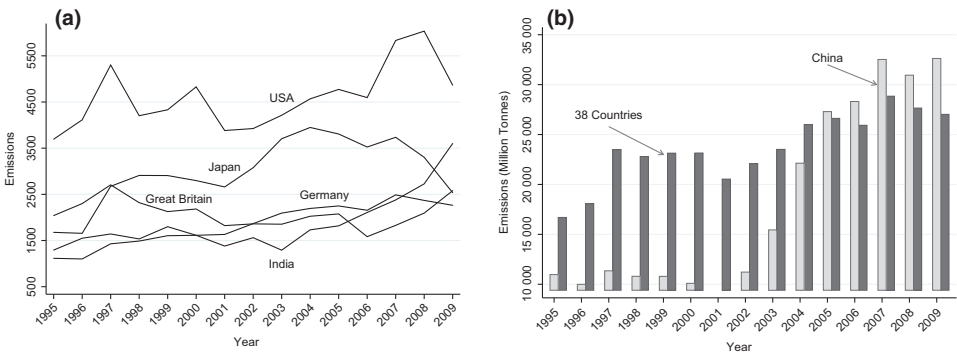


Figure 6 Origin of imported emissions (1000 Tonnes CO₂e).

the emissions imported from China as well as aggregate imported emissions from the other 38 countries. China accounted for around half of imported emissions.

The growth in imported emissions observed between 2002 and 2007 was essentially due to the increase in imports from China. Of the five countries reported in panel 6(a), only emissions imported from the United States and Japan noticeably increased. Aggregate imported emissions from all countries other than China increased from <17 million (CO₂e) in 1995 to around 30 million (CO₂e) in 2009, an increase of 50 per cent. In contrast, emissions imported from China increased from around 10 million CO₂e in 1995 to over 33 million CO₂e in 2009, an increase of over 210 per cent.

Imports from China contributed significantly to the growth of imported emissions illustrated in Figure 5. The share of imports coming from China increased from <5 per cent in 1995 to over 20 per cent in 2009. Most of the change in imports occurred after 2001. The growth in trade with China during this period corresponds to the growth in imported emissions as well as with the large persistent growth in consumption emissions reported in Figure 1.

Substantial increases in imports from China occurred in many sectors. The most substantial changes in terms of value and emissions content occurred in the electrical and optical sector, which increased by over 1000 per cent as did imports of electrical machinery. Textile imports increased by almost 300 per cent, whereas miscellaneous manufacturing increased by 900 per cent. These sectors were generally emission intensive (see tables in the Appendix S1). Moreover, there was an increase in the emission intensity in the sectors, which experienced large increases in imports from China.

Growth in the volume of Australian imports is not the entire story. The composition of imports in terms of sectors and exporters is also important. To get an overall measure of the intensity of emissions in Australian imports, we calculated the ratio of emissions to imports and report these in Figure 7 (the emission–import intensity ratio for each country is reported in the Appendix S1). The influence on emissions from the increase in imports from

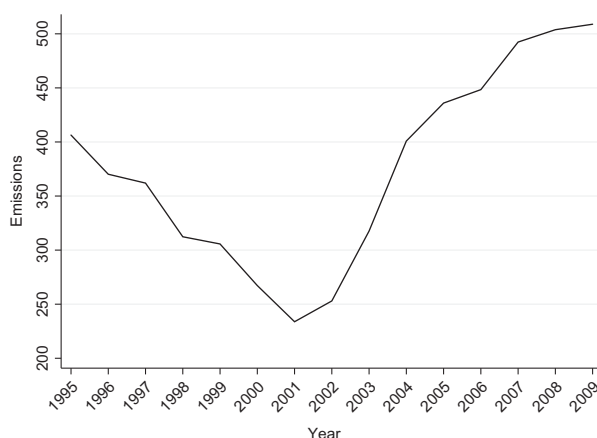


Figure 7 Emissions-to-imports intensity ratio (Tonne/Million AU\$, fixed prices).

China is also evident in Figure 7. The reversal of the decreasing trend in the emission–import intensity ratio coincides with the substantial growth of imports from China.

Imports from China were the most emission intensive compared to the other 38 countries (see tables in the Appendix S1). The high emission content of Chinese imports combined with Chinese imports comprising a larger share of Australian imports helps explain the increase in the emission intensity of Australian imports. Between 2001 and 2009, the share of Chinese imports increased by approximately 200 per cent.

To look further into the relationship between emissions and Australian economic activity as well as explore additional reasons for the differences between production and consumption emissions, we calculated the emission intensity of Australian exports as well as the emissions intensity of Australian consumption of Australian produced goods and service. Both of these measures are reported in Figure 8.

The U-shaped pattern observed in the import intensity measure is also observable in the export intensity measure. After at least 6 years of a declining emission-to-export ratio, the ratio started to increase, although the upswing was not as large compared to the import intensity measure nor did it have the same duration. The emission intensity of imports is larger than the measure for exports. Australia imported more goods from China than it exported to China, and the difference between imports and exports increased after 2001. These differences in the emission content of exports and imports help explain the different growth rates of production and consumption emissions.

To complete our analysis, we report in Figure 8, the emission intensity of Australian produced goods and services consumed in Australia. These emissions are included in both consumption and production emissions. The emission intensity of domestic consumption has been increasing at a relatively

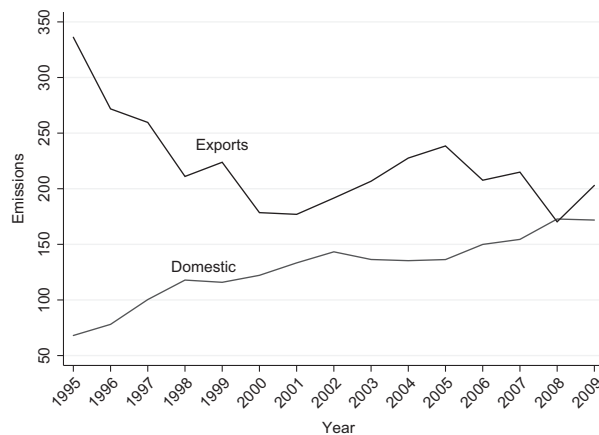


Figure 8 Emissions-to-exports and domestic consumption intensity ratios (Tonne/Million AU\$, fixed prices).

constant rate since at least 1995. Looking at each of the three intensity measures, we see that most of the changes in emissions occurred in international trade. Since 2001, the largest change occurred in imports and the reason for the large changes after 2001 was increasing trade with China.

5. Concluding remarks

Understanding linkages between economic activity and GHG emissions is necessary for developing effective GHG mitigation strategies and for monitoring the effectiveness of existing policies. We used a global input–output model to compute and analyse Australian consumption-based GHG emissions over a 15-year period, 1995–2009. Our measure accounts for variation in the emission intensity of production across sectors and countries by using sector- and country-specific emission factors for CO₂, CH₄ and N₂O. Our consumption-based measure of GHGs accounts for emissions embodied in international trade including trade in intermediate goods.

This research also contributed to the growing empirical literature arguing that consumption emissions should be monitored jointly with production emissions (see Barrett *et al.* (2013) for an analysis of UK emissions). Production (territorial) and consumption inventories track emissions produced by different economic activities. The information in these inventories is complementary, and analysing them jointly provides a more complete picture of GHG emissions. If Australian policymakers were to rely on production emissions to evaluate GHG mitigation efforts, they would conclude that the growth of Australian emissions has been slowing. However, the growth rate of Australian consumption emissions increased over the same period. Implementing coherent climate policy requires understanding the connection between consumption emissions and production emissions and the linkages to macroeconomic activity.

The benefits of tracking both production and consumption emissions are not specific to Australia. Table A5 in the Appendix S1 reports two sets of growth rates for production, consumption and imported emissions: growth rates for the period between 1995 and 2001 and from 2001 to 2007 (we do not include the financial crises). Production emissions tended to grow at a slower rate after 2001 for most western countries, while consumption emissions grew at a faster rate. The growth of consumption emissions is consistent with the growth in the volume of international trade, in particular, growth in trade from developing countries to developed countries (see also Peters *et al.* (2011)). The growth rate of imported emissions increased substantially in the post-2001 period.

Binding global climate agreements are not likely to be completed in the near future. GHG mitigation efforts will continue to rely on regional, national or incomplete international policies. Moreover, the volume of international trade is likely to continue to grow. Monitoring consumption emissions is important in this fragmented policy environment because of the potential for offshoring GHG emissions. This paper documented that the growth in imported emissions was a substantial contributor to the increase in the growth rate of Australian consumption emission. Barrett *et al.* (2013) report similar results for the UK. As international trade continues to grow with less developed economies (China, India, and Indonesia, for example), more emissions due to Australian economic activity will likely not be included in the Kyoto emissions accounting framework. The concern is that production emission could be falling (or the growth of emissions slowing) because countries are offshoring the production of emission intensive intermediate goods (see for example Levinson (2010) and Levinson and Taylor (2008)). Offshoring could increase global GHG emissions if production in the exporting country is relatively more emission intensive than domestic production.

Jointly tracking production and consumption emissions also provides the necessary data to identify the potential interdependent effects of environmental policies, and other economic policies, including trade policies, on emissions. Implementing policies directed at reducing production emissions could have the effect of increasing consumption emissions by altering relative costs. The substitution away from domestically produced goods to imported goods, which may be more emission intensive, is more likely if policies increase the costs of producing goods domestically relative to the costs of importing foreign-produced goods. Carbon leakage has the potential to mitigate the effectiveness of policies designed to curb GHG emissions (see Aichele and Felbermayr (2015)).

Our analysis of consumption emissions reinforces the global nature of the climate change challenge. The research established that Australian GHG emissions are linked not only to domestic economic activity but also to international production through international trade. Further research is needed to better understand the economic mechanisms linking production and consumption emissions, and the data reported in this paper can be used

to motivate these studies and also used in any analysis. For example, our study demonstrates that there is need to better understand the environmental implications liberalised trade. Complementary to understanding the sources of GHG emissions is mitigation policy. The research in this paper also emphasises that reducing GHG emissions, which are a global externality, requires cooperative policy because of the interdependence of domestic policy and internationally traded emissions. There is a need for further research into understanding the policy instruments available to address consumption-based emissions beyond simply tracking them.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Additional data.