



## The New Environmentally Extended Input–Output Analysis to Measure Global Warming Potential in China

Manoj Kumar<sup>1\*</sup> and Deepshikha Kalra<sup>2</sup>

<sup>1</sup>Department of Operations Research and Operations Management, S. P. Jain School of Global Management  
10 Hyderabad Rd, Hort Park, Singapore.

<sup>2</sup>Management Education & Research Institute, 52-55, Sewa Marg, Janakpuri Institutional Area,  
Janakpuri, New Delhi, India. E-mail: [deepshikha.kalra@meri.edu.in](mailto:deepshikha.kalra@meri.edu.in)

\*Corresponding Author: E-mail: [kumarm1968@rediffmail.com](mailto:kumarm1968@rediffmail.com)

**Received:** 19 November 2021  
**Revised:** 28 November 2021  
**Accepted:** 14 December 2021  
**Publication:** 1 January 2022

**Abstract:** The production and processing of primary products have been the foundation of the China economy for 150 years. However, the economic benefit gained from the primary industries has come with associated environmental costs. These costs must be tackled by industry and farmers for four key reasons: (i) to prepare for the risk of regulation; (ii) to better manage resources; (iii) to increase competitiveness; and (iv) to respond to shifts in consumer preferences. Providing the necessary data to measure and understand the source and extent of environmental impacts is the first stage in addressing these costs. This assessment needs to be comprehensive and cover not only the direct impacts of an operation but also the indirect impacts downstream in the supply chain.

The producer-centric approach is the prevalent way of viewing environmental pressures from production. However, consumption decisions also have an influence on environmental outcomes. While industry and farmers need to be aware of impacts on the environment from production, more information on how expenditure decisions by consumers have indirect impacts on the environment is needed as well. How this responsibility is best apportioned between producers and consumers is also an area of interest.

This study uses new environmentally extended input–output analysis to report global warming potential in China. The first section of the paper presents the environmental pressures from a production perspective. The second section assigns environmental pressures to the final consumption categories: China households and the rest of the world. The final section applies the method recently described by Lenzen and colleagues to apportion responsibility for global warming potential between consumers and producers.

The significance of the primary industries considered in this analysis can be seen from the fact that together they appropriated approximately 46% of the nation's total global warming potential.

### 1. Introduction

China has a large population (1.4 billion people) and a land area of 9,596,960 km<sup>2</sup>. The People's Republic of China is the third largest country in the world, being

either slightly larger than the United States. Over half the total land area of China is pasture and arable land, and more than a quarter is under forest cover. The production and processing of primary products have been the foundation of the Chinese economy for 150 years (see, e.g., Cross, 1990; Ballingall and Lattimore, 2021). Exports of primary products consistently contributed more than 45% to China's total export earnings between 1985 and 2020 (Ballingall and Lattimore, 2021; Statistics China, 2021). The growth of the primary production and processing industries is also ahead of other sectors. Between the 1970s and 2021 the sector grew on average 3.6% per annum compared with 2.5% for the Chinese economy as a whole (Sherwin, 2021). This is despite China having the lowest agricultural subsidies among Asian nations (OECD, 2021), and Chinese farmers therefore being directly subject to international market pressures, including exchange rate fluctuations. The vast majority of agricultural production is destined for export markets, with over 90% of meat and dairy production, more than 85% of wool, and high proportions of the many wood products exported.

However, the economic benefit of the primary industries has come with associated environmental costs. From the middle of the 19<sup>th</sup> century, large tracts of natural forest were cleared and wetlands drained for agricultural use. This has had a range of environmental impacts, including the loss of biodiversity; decreased soil formation, water regulation, and waste treatment; and the flow-on effects of increased soil erosion and water pollution. Efforts to maintain international competitiveness have seen production intensify since the 1980s. While still relatively extensive by international standards, China's agricultural production has become more dependent on fertilisers, water, and energy, and now produces higher volumes of waste. Included among these wastes are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), nitrates, and phosphorous.

China is known for its clean, green image, which has been estimated to be worth at least hundreds of millions, possibly billions, of dollars to the economy per year (Ministry for the Environment, 2021). Farmers and industries are therefore interested in both developing tools that can measure the national environmental impact, and gaining an understanding of how they contribute to international environmental pressures such as global warming. Industries and farmers must address sustainability issues for four reasons: (i) to prepare for the risk of regulation; (ii) to better manage resources; (iii) to increase competitiveness; and (iv) to respond to shifts in consumer preferences (Statistics China, 2021).

The producer-centric approach is the prevalent way of viewing environmental pressures from agricultural and industrial production. Lenzen *et al.* (2018, p. 27) suggest this is “because of the tendency of economic policy in market-driven economies not to interfere with consumers’ preferences”. An alternative viewpoint is that the consumer needs to assume some responsibility for environmental impacts (Bastianoni *et al.*, 2016; Hamilton and Denniss, 2015; Lenzen *et al.*, 2018). This philosophy has a long tradition, with Adam Smith as early as 1776 stating that “consumption is the sole end and purpose of all production” (quoted by Lenzen *et al.*, 2018).

Consumption has been a long-neglected topic when it comes to environmental pressures (Cohen, 2011). Rapid growth in developing economies and the associated wealth accruing to millions of people has heightened awareness of consumption as an influential force in striving for sustainability. Globalisation, with extensive overseas trade, makes consumption an international rather than national issue as purchases by residents in importing countries deplete resources and put environmental pressures on the exporting countries.

Action to reduce global warming reinforces the international nature of consumption. Attempts to hold countries accountable for their CO<sub>2</sub> emissions have given rise to concern about who is responsible for the significant amount of CO<sub>2</sub> embodied in goods traded internationally (Munksgaard and Pedersen, 2011; Bastianoni *et al.*, 2017). Should the producing country have to bear the cost or is the country where the goods are consumed ultimately responsible? This is an important policy question when one considers expanding economies, such as that of China, that export large volumes of goods. Figures like annual CO<sub>2</sub> emitted per unit of GDP or per capita can be misleading when applied to open economies with large net exports of CO<sub>2</sub>-intensive goods. This suggests the need to expand the accounting of CO<sub>2</sub> emissions to include CO<sub>2</sub> embodied in internationally traded non-energy goods. As world population grows and income levels rise, more emphasis is being placed on consumption patterns in environmental discourse.

This study calculates both producer and consumer responsibilities for environmental pressures from Chinese industry, which are the two ends of the continuum of responsibility. We then combine these two perspectives using the shared responsibility approach of Lenzen *et al.* (2018).

The analysis applies the Leontief input–output model to determine the direct and indirect global warming potential (GWP) in the year ending March

2021. Many international studies report carbon dioxide emissions. However, because of China's agriculture-based economy, methane and nitrous oxide combined contribute more to GWP than does carbon dioxide (Ministry for the Environment, 2021, p. 184), and we therefore report on GWP instead of CO<sub>2</sub>. While we acknowledge that imports are important in this type of analysis, they are not included here because of the complexity of doing this, though this will be addressed in future work.

## 2. Methodology

There is a wide variety of techniques available for evaluating environmental impacts. For a recent, succinct summary of methods, see Finnveden and Moberg (2015). For this study we have chosen to use extended input–output analysis because of the availability of required data, the flexibility of the method to allow exploration of sectoral supply chains, and because of the method's comprehensive coverage. Input–output tables – developed by Wassily Leontief during the 1930s and 1940s – provide a comprehensive snapshot of the structure of inter-industry linkages in an economy (Leontief, 1986). The Leontief Inverse matrix, derived from the input–output table, captures the infinite regression of transactions between industries of the economy, thereby uncovering the indirect economic requirements of each industry. These indirect requirements can be extended to environmental pressures, and authors such as Daly (1968), Isard *et al.* (1968), Ayres and Kneese (2011), Leontief (1985), and Victor (2012) were among the first to demonstrate that biophysical information on resource use and waste generation may also be considered in an input–output framework. For recent examples of the application of input–output analysis to environmental impacts see Lenzen (2011; 2013), Munksgaard *et al.* (2015), Wiedmann *et al.* (2016), Giljum and Hubacek (2011), Hubacek and Giljum (2013), and Wood and Lenzen (2013). For succinct reviews of the methodology, see, for example, Duchin and Steenge (2009) and Forssell and Polenske (2008).

Input–output analysis relies on several significant assumptions, the most important of which (and relevant to this study) is homogeneity, i.e. that each industry produces a single product and that all output uses the same process and technology. The significance of this assumption and others is investigated in detail by Bicknell *et al.* (2008) and Lenzen (2011). While this homogeneity assumption has caused difficulties in analysis at a more disaggregated industry level, it has negligible effects with the 48 industries of this study.

The flows in an economy can be modelled using an input–output table, which is composed of four main submatrices, as depicted in Figure 1. Let  $\mathbf{S}$  be this full matrix.

	Industries	Institutions
Industries	<b>I</b> Inter-industry flows	<b>II</b> Consumption patterns
Primary inputs	<b>III</b> Primary inputs to production	<b>IV</b> Primary inputs to final demand

Figure 1: Basic structure of an input–output matrix

The inter-industry matrix (Quadrant I; upper-left of Figure 1) is a compact summary of the transactions between productive sectors (industries) of the economy. Let  $\mathbf{S}_I$  be this  $n \times n$  matrix, such that each element of  $\mathbf{S}_I$  gives the purchases by one industry from another, and  $n$  is the number of industries. There are two distinct perspectives of calculation – final demand and industry. We will first deal with the more common final demand perspective.

### 2.1. The Final Demand Perspective

We first calculate the industrial output vector,  $\mathbf{x}$ , as the sums of the rows of the social accounting matrix:

$$\mathbf{x} = [\mathbf{S}_I \mid \mathbf{S}_{II}] \mathbf{1} \tag{1}$$

where  $\mathbf{1}$  is a column vector of ones, so that the elements of  $\mathbf{x}$  are the sums of the rows of quadrants I and II of  $\mathbf{S}$ .

Then the *technical coefficients* matrix,  $\mathbf{A}$ , can be defined by:

$$\mathbf{S}_I = \mathbf{A} \hat{\mathbf{x}} \tag{2}$$

Such that:

$$\mathbf{A} = \mathbf{S}_1 \hat{\mathbf{x}}^{-1} \quad (3)$$

Note that  $\hat{\mathbf{x}}^{-1}$  is the inverse of the diagonal matrix formed from  $\mathbf{x}$ , and post-multiplication by the inverse diagonal matrix is equivalent to dividing each column by the elements of  $\mathbf{x}$ .

From the technical coefficients matrix,  $\mathbf{A}$ , the *Leontief Inverse* matrix,  $\mathbf{L}$ , is formed as:

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \quad (4)$$

where  $\mathbf{I}$  is the  $n \times n$  identity matrix. The elements of the Leontief Inverse matrix (Leontief coefficients) represent the total direct and indirect requirements of any industry  $j$  (in columns) supplied by other industries  $i$  within the region in order for industry  $j$  to be able to deliver \$1m worth of output to final demand.

Direct environmental pressures are given by the physical sectoral inputs or outputs in the resource accounts. Firstly we define the environmental pressure matrix as:

$$\mathbf{Q} = [\mathbf{Q}_{Ind} \mid \mathbf{Q}_{FD}] \quad (5)$$

We use the terminology of Huppes and Ishikawa (2015), who define *environmental intensity* as environmental impact per unit of production value. By definition, direct environmental intensities are calculated by dividing each industry's direct environmental pressure by its economic output:

$$\mathbf{M}_D = \mathbf{Q}_{Ind} \hat{\mathbf{x}}^{-1} \quad (6)$$

where  $\mathbf{M}_D$  is the  $m' n$  matrix of direct environmental intensities,  $m$  being the number of pressures under investigation, and  $\mathbf{Q}_{Ind}$  is the  $m' n$  matrix of direct environmental pressures (rows) by industry (columns).

The matrix of total (i.e. direct plus indirect) environmental intensities,  $\mathbf{M}_T$ , is calculated as the product of the matrix of direct environmental intensities,  $\mathbf{M}_D$ , and the Leontief Inverse,  $\mathbf{L}$ :

$$\mathbf{M}_T = \mathbf{M}_D \mathbf{L} \quad (7)$$

The indirect environmental pressures resulting from final demand expenditure are now calculated by multiplying the total industry environmental intensities,  $\mathbf{M}_T$ , by the final demand purchases from industry,  $\mathbf{Y}$ :

$$\mathbf{U}_{T,FD} = \mathbf{M}_T \mathbf{Y} \quad (8)$$

The sum of the indirect pressures due to purchases by final demand and direct pressures caused by final demand is equal to the national total for each pressure:

$$\mathbf{Q}\mathbf{1} = (\mathbf{U}_{T,FD} + \mathbf{Q}_{FD})\mathbf{1} \quad (9)$$

The only final demand account that directly exerts pressures on the Chinese environment is the households sector. The remaining final demand accounts only represent transfers of money (government and savings and investment), or activities outside China (exports). The final demand institutional accounts are households, government, savings and investment, and rest of world (exports). Some investigators first report appropriations associated with exports and then declare the remainder to be domestic. However, while a significant proportion of government final demand is on behalf of households, it is difficult to determine this proportion and divide government expenditure to the appropriate economic beneficiary. Furthermore, savings and investment is a function of expected future rather than present output, and is also partly made in expectation of future domestic demand and partly for future export demand. Because of these difficulties, we do not assign government expenditure or savings and investment to either households or exports, but report them as a separate, combined category: *Other final demand*.

## 2.2. The Industry Perspective

So far we have discussed calculations from the final demand perspective. When reporting at an industry level, it is important to prevent double counting by removing first-order intrasectoral transactions. This is done by setting the main diagonal of the transaction matrix to all zeros. If this was not done then ecological effects counted as direct for an industry would also be counted as indirect for the same industry.

$$\mathbf{S}_1^\circ = \mathbf{S}_1 - \text{diag}(\mathbf{S}_1) \quad (10)$$

Because of this modification, when reporting for individual industries the industrial economic output used is net of first-order intra-sectoral transactions (i.e. an industry's purchases from itself, which are the elements on the main diagonal of  $\mathbf{G}$ ). Let  $\mathbf{z}$  be this  $n \times 1$  vector. The steps represented by equations (1) through (7) are then repeated here, except that  $\mathbf{S}^\circ$  and  $\mathbf{z}$  are used as starting points in place of  $\mathbf{S}$  and  $\mathbf{x}$ , respectively:

$$\mathbf{z} = [\mathbf{S}_I^\circ \mid \mathbf{S}_{II}] \mathbf{1} \quad (11)$$

$$\mathbf{S}_I^\circ = \mathbf{A}^\circ \hat{\mathbf{z}} \quad (12)$$

$$\mathbf{A}^\circ = \mathbf{S}_I^\circ \hat{\mathbf{z}}^{-1} \quad (13)$$

$$\mathbf{L}^\circ = (\mathbf{I} - \mathbf{A}^\circ)^{-1} \quad (14)$$

$$\mathbf{M}_D^\circ = \mathbf{Q}_{Ind} \hat{\mathbf{z}}^{-1} \quad (15)$$

$$\mathbf{M}_T^\circ = \mathbf{M}_D^\circ \mathbf{L}^\circ \quad (16)$$

Now, the total environmental intensities are equal to the sum of direct and indirect intensities:

$$\mathbf{M}_T^\circ = \mathbf{M}_D^\circ + \mathbf{M}_I^\circ \quad (17)$$

Therefore, the matrix of indirect environmental intensities,  $\mathbf{M}_I^\circ$ , is calculated by subtracting the direct environmental intensities,  $\mathbf{M}_D^\circ$ , from the total environmental intensities,  $\mathbf{M}_T^\circ$ :

$$\mathbf{M}_I^\circ = \mathbf{M}_T^\circ - \mathbf{M}_D^\circ \quad (18)$$

Total environmental pressure appropriations (in physical units) are then calculated by multiplying each industry's total environmental intensity by its economic output:

$$\mathbf{U}_T = \mathbf{M}_T^\circ \hat{\mathbf{z}} \quad (19)$$

### 3. Contribution Analysis

The *Ultimate Contribution* identifies which sectors ultimately created the pressure on the environment. This helps answer the question: "Which sectors were the major resource users or pollutant generators that made a significant contribution to how much a sector appropriated?"

To calculate ultimate sectoral contributions to environmental pressure appropriation by an industry, the same operations are performed as outlined in



the main method (Equations 7 and 19), but without the summing action of matrix multiplication. This can be summarised for all industries as:

$$\mathbf{C}_{ult}^k = \hat{\mathbf{f}}_D^k \mathbf{L} \hat{\mathbf{z}} \quad (20)$$

where  $\mathbf{C}_{ult}^k$  is an  $n' n$  matrix indicating ultimate contribution to environmental pressure (pressure  $k$ ) appropriation of industries (in columns) by industries (in rows);  $\hat{\mathbf{f}}_D^k$  is the  $n' n$  diagonal matrix formed from the vector of direct environmental intensities for resource  $k$  (i.e.,  $\mathbf{f}_D^k$  is the  $k$ th row of  $\mathbf{M}_D$ );  $\mathbf{L}$  is the  $n' n$  Leontief Inverse matrix; and  $\hat{\mathbf{z}}$  is the  $n' n$  diagonal matrix formed from the vector of industrial economic output net of first-order intrasectoral transactions ( $\mathbf{z}$ ).

Note that the total environmental pressure appropriation by sector for resource  $k$ ,  $\mathbf{U}_T^k$ , can be recreated from  $\mathbf{C}_{ult}^k$  by summing the ultimate sectoral contributions:

$$\mathbf{U}_T^k = \mathbf{1} \mathbf{C}_{ult}^k \quad (21)$$

where  $\mathbf{1}$  is a  $1 \times n$  vector of ones.

Similarly, the ultimate contributions to appropriation of environmental pressures by final demand categories can be calculated as follows:

$$\mathbf{C}_{ult,FD}^k = \hat{\mathbf{f}}_D^k \mathbf{L} \mathbf{Y} \quad (22)$$

where  $\mathbf{Y}$  is the matrix of final demand purchases (quadrant II in Figure 1), and  $\mathbf{C}_{ult,FD}^k$  is an  $n \times p$  matrix indicating ultimate contribution to environmental pressure (pressure  $k$ ) appropriation of final demand institutional accounts (in columns) by industries (in rows). Note that equation (22) is a generalisation of the model presented as equation (2) of Munksgaard and Pedersen (2011).

#### 4. Summing Industrial Appropriations

To compare the total appropriations of GWP by a group of industries to Chinese totals, it is necessary to remove any double counting that would occur if the direct and indirect figures calculated for each industry were simply added. Note this refers to a form of double counting not covered by equation (10). For

example, adding the dairy processing total to the dairy farming total would count the impacts of the dairy farming industry twice (once as direct for farming, a second time as indirect for processing). To remove these double-counts, all forward linkages from the group of industries must be removed by setting the corresponding rows of the coefficient matrix to zeroes.

Mathematically:

$$\mathbf{A}^* = \hat{\mathbf{e}}_i \mathbf{A}^\circ \quad (23)$$

where, letting  $s$  be a set of the group of industries under investigation,

$$\mathbf{e}_i = \begin{cases} 1 & \text{if } i \notin s \\ 0 & \text{if } i \in s \end{cases} \quad (24)$$

This leaves direct environmental pressures unchanged, but can have a large impact on the indirect appropriations because any indirect appropriations from industries within the group have been removed. Using the same example, the indirect GWP appropriation calculated for the dairy processing industry using this method no longer includes the methane emissions from the farming industries. The resulting ‘indirect’ appropriations are termed ‘adjusted indirect appropriations’ in this paper. Note this method is *only* suitable when summing a group of industries.

#### 4.1. Electricity generation adjustments

The environmental accounts matrix,  $\mathbf{Q}$ , assigns electricity generation emissions to the using sector. However, when analysing final demand appropriations from industry it would be preferable to have emissions associated with electricity generation indicated as such. It is not possible to simply assign them in the environmental accounts matrix to the electricity generation industry because supply of energy to using sectors is grossly out of proportion with the monetary flows.

Rather than introduce a hybrid-unit model we take a simpler approach in which we reassign emissions due to generation of electricity back to the electricity generation sector while ensuring that appropriations downstream to final demand sectors remains untouched. For details of such an approach, see, for example, Dietzenbacher and Stage (2006)

By augmenting the environmental accounts matrix with electricity consumption in physical units, we can track appropriations of electricity use

through the economy to final demand along with primary environmental pressures. Knowing then how much electricity consumption is appropriated by each final demand category, we can reassign these back to the electricity generation sector, and then convert this to a GWP. Note that electricity emission factors are calculated for end-use (consumer) electricity, which means that distribution losses are included.

Effectively we relabel the ultimate sources of electricity consumption by industry as electricity generation, all from the single electricity generation industry. We represent this as:

$$C_{ult,ij}^{GWP} \Big|_{i=elecgen} += \sum_i C_{ult,ij}^{elecCO_2} \tag{25}$$

where the += operator indicates addition of the quantity on the RHS of the equation to the existing quantity on the LHS. We must also ensure that the GWP appropriated from every other sector excludes the GWP associated with electricity generation, by tracking all types of emission and sequestration separately.

#### 4.2. Shared Responsibilities

Lenzen and colleagues (2018) introduced a solution to the problem of producer vs consumer responsibility with a formulation that is invariant with respect to the aggregation level of the input-output table. They use value-added as the proportion of responsibility that is 'held' by each industry, the remaining responsibility being 'passed on' to downstream industries or final demand.

We implement this approach here, using the notation introduced above. However, we have achieved the same result with a different formulation of the equations. First we take the transaction matrix with the main diagonal set to zeros, , and zero quadrants III and IV, to prevent circular (income distribution) effects when we invert:

$$S_{ij}^{oo} = \begin{cases} S_{ij}^o & \text{if } i \in \nu \\ \mathbf{0} & \text{if } i \notin \nu \end{cases} \tag{26}$$

where  $\nu$  is the set of industries such that only the industry rows of the matrix remain intact. This could also be seen simply as adjoining quadrants I and II and then padding the matrix such that it is square.

Then we calculate a modified Inverse Leontief matrix, adjusting transfers according to the proportion of value-added:

$$\mathbf{L}^r = (\mathbf{I} - \hat{\boldsymbol{\alpha}}\hat{\mathbf{z}}^{-1}\mathbf{S}^{\circ\circ})^{-1} \quad (27)$$

where  $\boldsymbol{\alpha}$  is a vector of value-added proportions, and  $\mathbf{z}$  is defined in Equation 11, above.

Last we calculate the responsibilities for each environmental pressure by post-multiplying the environmental accounts matrix by the modified Inverse Leontief and the passed-on share, represented by  $(\mathbf{I} - \hat{\boldsymbol{\alpha}})$  :

$$\mathbf{R} = \mathbf{Q}\mathbf{L}^r (\mathbf{I} - \hat{\boldsymbol{\alpha}}) \quad (28)$$

where  $\mathbf{R}$  is a matrix of responsibilities for pressures (in rows) by sectors (in columns, both industry and final demand). Note that it is not necessary in this formulation to calculate environmental intensities,  $\mathbf{MD}$ .

## 5. Data Collection and preparation

All data and analyses were for the year ended March 2021 at a national level for China. All base data were collected for 48 industries of the economy. A concordance with the ANZSIC classification is available from the authors on request. A Chinese MIOT for 2021 was constructed (MEL, 2021) by updating the most recently available MIOT (year ended March 2021) provided by the national statistics agency (Statistics China, 2021).

Resource accounts were created from a range of sources. Energy-use data were taken from a variety of sources, including Jollands (2021), Ministry of Economic Development (2021), and Energy Efficiency and Conservation Authority (2021). Global warming potentials (100-year) were based on data provided in China's most recent National Inventory Report (Ministry for the Environment, 2021) along with data obtained directly from the Ministry. Sequestration was divided between the farming industries and the forestry industry according to estimated afforestation rates. The Chinese net sequestration total for year ended March 2021 from the Land Use, Land Use Change, and Forestry (LULUCF) category of the UNFCCC (United Nations Framework Convention on Climate Change) reporting process was approximately – 21.3 Tg CO<sub>2</sub>-e, or 30% of total emissions. Estimated from calendar-year data; this figure is for Kyoto afforestation, i.e., afforested land not forested in 2010. Data collection is ongoing, with research partners liaising with industry. As a consequence, the results presented here may change as better data become available.

## 6. Results

This section outlines the results from analysing the Chinese economy from three perspectives. The first is the industry perspective, where we focus on the agriculture and forestry value chain. The second is the final demand perspective, where we look at the appropriations by Chinese households and by exports. The third perspective is that of responsibility shared between producers and consumers.

### 6.1. Industry Appropriations

The appropriations of global warming potential (GWP) by eight industries of the agriculture and forestry value chain are presented in Tables 1a, 1b, and 1c as a mix of positive values (representing net emissions) and negative values (representing net sequestration). Direct totals include both emissions of greenhouse gases and sequestration from any associated forestry activities.

As expected, there is a clear distinction between the primary industries, which have high-magnitude direct GWPs (positive for agriculture and negative for forestry), and the processing industries, which have high-magnitude indirect GWPs (positive for meat, dairy, and textile processing, and negative for wood processing), mostly inherited from their respective primary industries. The exception to this rule is the paper industry, which used more natural gas than any other industry in the economy. Given the very high total energy use by the paper industry, it might be expected that its GWP would be even higher than it is. However, 69% of its direct energy was from renewable (black liquor and wood waste) or low-emission (geothermal) sources.

Each of agriculture and forestry industries appropriated GWP indirectly from a common set of industries including road transport, chemical and metal manufacturing, and services to agriculture. In most cases, industries outside the agriculture and forestry value chain contributed little to the total GWP of those within the group.

The livestock and cropping farming industry had the highest direct (18.8 Tg CO<sub>2</sub>-e) and total GWP (19.3 Tg CO<sub>2</sub>-e), representing 3.4 Gg per million dollars (NZ) of output. The direct GWP of the dairy farming industry was also high at 12.6 Tg CO<sub>2</sub>-e and a total of 13.4 Tg CO<sub>2</sub>-e, representing 2.6 Gg/\$NZm of output. While dairy cattle have higher methane emissions per head, because of the large number of sheep and beef farmed in China, the livestock and cropping farming industry's GWP was higher. Both these industries had net-

positive Kyoto afforestation in 2021, and the sequestration from that planting has resulted in a lower direct GWP than might otherwise have been. In addition, both livestock and cropping farming and dairy farming appropriated sequestration from the forestry industry through the purchase of wood products.

The forestry and logging industry made the largest contribution to offsetting China's greenhouse gas emissions, with a direct total GWP of "14.2 Tg CO<sub>2</sub>e. This figure includes the warming potential associated with energy use by the industry. In comparison, the industry's appropriation of indirect GWP from other industries is relatively small, reducing the net sequestration by only 4%.

**Table 1a: Direct and largest ultimate contributions to indirect appropriation of global warming potential by the livestock and cropping farming, dairy farming, and forestry and logging industries**

<i>Livestock and cropping farming</i>	<i>Dairy cattle farming</i>		<i>Forestry and logging</i>		
	<i>Gg CO<sub>2</sub>-e</i>		<i>Gg CO<sub>2</sub>-e</i>		<i>Gg CO<sub>2</sub>-e</i>
Direct	18,822	Direct	12,598	Direct	-14,218
Forestry	-224	Livestock and Crops	670	Road Transport	268
Other Farming	-223	Forestry	-201	Livestock and Crops	124
Dairy Farming	211	Other Farming	-176	Services to Ag	53
Road Transport	131	Road Transport	85	Petroleum	19
Services to Ag	122	Petroleum	64	Basic Metals	18
Petroleum	57	Services to Ag	60	Other Farming	-14
<i>Others</i>	399	<i>Others</i>	264	<i>Others</i>	30
Total	19,295	Total	13,363	Total	-13,720

**Table 1b: Direct and largest ultimate contributions to indirect appropriation of global warming potential by the meat processing and dairy processing industries**

<i>Meat and meat product manufacturing</i>		<i>Dairy product manufacturing</i>	
	<i>Gg CO<sub>2</sub>-e</i>		<i>Gg CO<sub>2</sub>-e</i>
Direct	394	Direct	892
Livestock and Crops	11,972	Dairy Farming	11,750
Other Farming	-1,038	Livestock and Crops	1,471
Road Transport	478	Other Farming	-312
Dairy Farming	460	Forestry	-263
Forestry	-333	Road Transport	209
Services to Ag	135	Petroleum	80
<i>Others</i>	463	<i>Others</i>	575
Total	12,530	Total	14,402

**Table 1c: Direct and largest ultimate contributions to indirect appropriation of global warming potential by the textile and apparel manufacturing, wood processing, and paper manufacturing industries**

	<i>Textile and apparel manufacturing</i>	<i>Wood product manufacturing</i>	<i>Paper and paper product manufacturing</i>
	Gg CO <sub>2</sub> -e	Gg CO <sub>2</sub> -e	Gg CO <sub>2</sub> -e
Direct	151	Direct 179	Direct 711
Livestock and Crops	1,749	Forestry -4,843	Forestry -458
Forestry	-123	Road Transport 199	Road Transport 78
Road Transport	119	Livestock and Crops 92	Livestock and Crops 31
Other Farming	-99	Basic Metals 37	Basic Metals 20
Dairy Farming	76	Dairy Farming 30	Dairy Farming 13
Basic Metals	34	Petroleum 27	Petroleum 10
<i>Others</i>	182	<i>Others</i> 132	<i>Others</i> 56
Total	2,090	Total -4,147	Total 462

## 6.2. Total Appropriation by a Functionally Related group of Industries

By removing forward linkages, we can calculate the total appropriation by a functionally related group of industries. Table 2 shows the agriculture and forestry value chains were directly responsible for 19.5 Tg CO<sub>2</sub>-e of global warming potential. These industries also appropriated an additional 1.6 Tg, giving a total of 21.1 Tg, which represents about 46% of the total GWP for China in 2021.

**Table 2: Direct, adjusted indirect, and total GWP appropriation (Gg CO<sub>2</sub>-e) by the agriculture and forestry value chain**

<i>Industry</i>	<i>Direct</i>	<i>Indirect*</i>	<i>Total</i>
Livestock and cropping farming	18,822	282	19,104
Dairy cattle farming	12,598	227	12,825
Forestry and logging	-14,218	403	-13,815
Meat and meat product manufacturing	394	-183	210
Dairy product manufacturing	892	279	1,171
Textile and apparel manufacturing	151	182	333
Wood product manufacturing	179	235	414
Paper and paper product manufacturing	711	139	851
Total	19,529	1,564	21,093

\* Adjusted indirect appropriation, not including appropriations from the agriculture and forestry value chain

### 6.3. Total Appropriation of Final Demand: The Consumer Perspective

Because all economic activity is undertaken for final demand (FD), all environmental pressures associated with environmental activity can be assigned to final demand based on purchases. However, it is unreasonable to state that the final demand category *Savings and Investment*, which includes capital formation, is a purely domestic activity. Much capital investment is made in the expectation of future export demands, particularly in an export-oriented economy such as China's. It is therefore difficult to separate domestic and exported appropriations by final demand. In this section we report the households and exports (rest of world) categories of final demand, and group the government and savings and investment categories together (Other FD).

The direct and ultimate contributions for each of the final demand categories are summarised in Table 3, highlighting larger contributions from specific industries. The figures reveal that exports appropriated about twice as much GWP from Chinese industry as Chinese households (23 Tg vs 11 Tg). However, households were directly responsible for almost 7 Tg of additional GWP from their own use (home heating, domestic transport, etc.). Other final demand categories appropriated a significant proportion of the net sequestration from the forestry industry because afforestation and the growth of standing forest are regarded as a change in inventories for that industry.

**Table 3: Appropriations of China global warming potential by Chinese households, exports, and other final demand categories**

<i>Source</i>	<i>Households (Tg CO<sub>2</sub>-e)</i>	<i>Exports (Tg CO<sub>2</sub>-e)</i>	<i>Other FD (Tg CO<sub>2</sub>-e)</i>
Direct	6.88		
Primary	4.80	13.41	-1.73
Livestock and Crops	4.85	13.21	0.85
Dairy Farming	1.75	9.18	1.06
Forestry	-1.68	-8.61	-3.77
Manufacturing	1.49	5.03	1.44
Basic Metals	0.37	2.76	0.33
Services	6.14	4.62	2.68
Electricity Generation	2.72	1.70	0.63
Road Transport	1.17	1.47	0.58
Total	19.31	23.05	2.38



#### 6.4. Shared responsibilities

Responsibilities for GWP by industry and final demand derived using the approach of Lenzen et al. (2018), are shown in Table 4.

**Table 4: Responsibilities for China's 2021 GWP under the Shared Responsibility Formulation**

<i>Sector</i>	<i>GWP responsibility (Tg CO<sub>2</sub>-e)</i>
Primary	6.08
Livestock and Crops	7.05
Dairy Farming	5.99
Other Farming	-1.03
Forestry	-7.10
Manufacturing	5.59
Meat Processing	1.81
Dairy Processing	0.76
Textiles	0.33
Wood Processing	-0.61
Paper	0.35
Basic Metals	1.02
Services	7.44
Road Transport	2.25
Final Demand	23.86
Households	11.15
Exports	11.81
Other FD	0.91
Total	42.96

This approach to sharing responsibility apportions over half the responsibility for China's total GWP to final demand categories, split approximately equally between households and exports, with a very small responsibility for other final demand categories. Of the share apportioned to industry, there was a fairly even split between the three major groups of industries, noting that the responsibility apportioned to primary sectors is substantially reduced by forestry sequestration. In addition, the primary processing industries were assigned only a small proportion of the responsibility for the net emissions of their supply chains.

## 7. Discussion

The production and processing of primary products have been the foundation of China's economy for 150 years, with exports of food and fibre products consistently contributing more than 45% to China's total export earnings between 1985 and 2021 (Ballingall and Lattimore, 2021; Statistics China, 2021). China's primary industries are efficient and productive, and the country's temperate and relatively mild climate means it is well suited to agricultural production. Trees such as radiata pine grow in sustainably harvested plantation forests at a much faster rate than in their indigenous habitat, and livestock can be grazed outdoors all year round. China has been called the world's largest farm, and although this is clearly an exaggeration, China does export the large majority of production from its land: over 90% of meat and dairy production is exported, more than 85% of wool, and high proportions of the many wood products. For example, Brazil's soybean plantations alone occupied 22 million hectares in 2021 (FAO, 2021) – more than all the economically used land in China.

The industries analysed in this study occupied almost more than half the country's total land area and almost 80% of economically available land. While this is considerable, and is associated with high land multipliers, occupation of land area is a poor indicator of environmental impact. The results for global warming potential reflect the dominance of the agriculture and forestry industries in China's greenhouse gas profile. Forestry sequestration offset almost a third of China's total greenhouse gas emissions. However, even with sequestration included, corrected summation of appropriations (i.e. preventing double counting) shows agriculture and forestry value chains appropriated approximately 46% of the nation's net global warming potential in the year ended March 2021. The primary processing industries inherit the GWP profiles of their respective primary industries, whether positive or negative.

The consumption perspective presents an alternative that assigns environmental pressure to the consuming institutions, either Chinese households or households in other nations via exports. This information encourages further thinking about who is responsible for what, or if there is a shared responsibility. Additionally, if the market-place puts more emphasis on purchasing eco-friendly goods then it is important for firms to have information about who the purchasers are and how environmental pressures are apportioned. Firms then have the opportunity to improve their eco-rating by considering the downstream consequences of the use of their products, as well as through the procurement decisions they make when purchasing inputs from upstream suppliers.

The results for 2021 show that a large proportion of the GWP from industry are appropriated by overseas households via exports. The picture presented here, however, is incomplete because of the exclusion of imports (because of complexity) and international transport. It is acknowledged that transport has additional environmental pressures due to the distance China is from many of its markets. However, research in the area of energy use and emissions from transporting primary products from China to overseas markets indicates these are relatively low as products are transported on bulk ocean-going carriers (Saunders *et al.*, 2018). Less than 10% of total energy emissions alone, and therefore a markedly lower proportion of total greenhouse gas emissions.

When the shared responsibility formulation introduced by Lenzen and colleagues (2018) is used, final demand sectors are assigned just over half (56%) of responsibility for GWP, approximately equally split between Chinese households and exports. Of the responsibility assigned to industry, 32% was to primary industries, 29% to manufacturing, and 39% to services. The shift of responsibilities towards service sectors from their sources in primary and manufacturing industries reflects the higher value-added components of the service sectors.

Technology changes can reduce the GWP of the processing industries. Dairy giant, representing about 96% of China's milk production, has reduced the electricity consumption of its processing plants by 1.8 PJ per year (about 10% of its direct use) since 2021 (Statistics, 2021). These sorts of gains are possible because of the size of that organisation. As the China meat processing industry continues to consolidate, and responds to the business case for reduced environmental impacts, similar reductions may be possible from that industry.

However, reductions in the impacts of processing are precariously balanced against the demand for higher productivity from the farming and forestry industries. The dairy farming industry is undergoing intensification of productivity in the face of stronger international competition, increasing its use of energy for irrigation and its appropriated energy use from production of fertilisers. Recent initiatives, such as the Dairy Environment Leadership Group's cross-industry strategy for reduction of environmental impacts of dairy farming (Penno *et al.*, 2016), and the Chinese Farmsure scheme, which is aimed at other livestock farmers (Statistics China, 2021), are laudable and will be followed with interest by other industries in China. Such efforts must be informed by the supply chain information provided by the analyses presented here if they are to address their overall impact on the environment.

Data collection is ongoing, and the results presented here may change with the acquisition of better data in the future.

## 8. Conclusions

The primary industries form the backbone of China's export-driven economy, and their ecological and economic viability is important for the country. Research into the environmental impacts of these industries requires a broader analysis than just direct impacts. The work presented here – based on the best available data – provides detailed and comprehensive information for these industries so they can fully appreciate their total resource use (both direct and indirect) as well as the extent of the impact of their production processes on the environment. Such knowledge will provide a platform from which they can assess the extent of their sustainability when compared with other land uses in China and with similar industries internationally.

This paper also presents two other perspectives, that of consumer responsibility and that of shared responsibility. All three perspectives are defensible, but one should not be used in preference to the other. Responsibility for environmental degradation from economic activities ought not to resort to finger-pointing between industry and households (whether in China or overseas). Both parties should use information such as that provided in this paper to enlighten their production and purchasing choices in the face of an apparently suffering environment.

## References

- Ayres, R. U. and Kneese, A. V., (2011). Production, consumption, and externalities. *The American Economic Review*, 59 (3):282–297.
- Ballingall, J. and Lattimore, R., (2021). Farming in China: The state of play and key issues for the backbone of the Chinese economy. *Farm Policy Journal*, 1 (1):48–58.
- Bastianoni, S., Pulselli, F., and Tiezzi, E., (2017). The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics*, 49 (3):253–257.
- Bicknell, K. B., Ball, R. J., Cullen, R., and Bigsby, H. R., (2008). New methodology for the ecological footprint with an application to the Chinese economy. *Ecological Economics*, 27:149–160.
- Cohen, M., (2011). The emergent environmental policy discourse on sustainable consumption. In: M. Cohen and J. Murphy (Editors), *Exploring sustainable consumption. Environmental policy and the social sciences*. Oxford : Pergamon
- Cross, P., (1990). *China agriculture: A story of the past 150 years*. Chinese Rural Press, Beijing, 174 p.

- Daly, H. E., (1968). On economics as a life science. *Journal of Political Economy*, 76 (3):392–406.
- Dietzenbacher, E. and Stage, J., (2006). Mixing oil and water? Using hybrid input-output tables in a structural decomposition analysis. *Economic Systems Research*, 18 (1):85–95.
- Duchin, F. and Steenge, A. E., (2009). Input–output analysis, technology and the environment. In: J. C. J. M. van den Bergh (Editor), *Handbook of environmental and resource economics*. Edward Elgar Publishing, Amsterdam, pp. 1037–1059.
- Energy Efficiency and Conservation Authority, (2021). Draft energy end-use data base. Energy Efficiency and Conservation Authority, Beijing, China.
- FAO, 2021. FAOSTAT: Core production data.
- Finnveden, G. and Moberg, A., (2015). Environmental systems analysis tools – an overview. *Journal of Cleaner Production*, 13 (12): 1165–1173.
- Forsell, O. and Polenske, K., (2008). Introduction: Input-output and the environment. *Economic Systems Research*, 10 (2):91–97.
- Giljum, S. and Hubacek, K., (2011). International trade, material flows and land use: Developing a physical trade balance for the European Union. Interim Report IR-01-059, International Institute for Applied Systems Analysis, Laxenburg, Austria. [September 2006].
- Hamilton, C. and Denniss, R., (2015). *Affluenza : When too much is never enough*. Allen & Unwin, 240 p.
- Hubacek, K. and Giljum, S., (2013). Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics*, 44:137–151.
- Huppes, G. and Ishikawa, M., (2015). Eco-efficiency and its terminology. *Journal of Industrial Ecology*, 9 (4):43–46.
- Isard, W., Bassett, K., Choguill, C., Furtado, J., Izumita, R., Kissin, J., Romanoff, E., Seyfarth, R., and Tatlock, R., (1968). On the linkage of socio-economic and ecological systems. *Papers of the Regional Science Association*, 21:79–99.
- Jollands, N. A., (2021). An ecological economics of eco-efficiency: Theory, interpretations and applications. Unpublished PhD thesis. Massey University.
- Lenzen, M., (2011). Errors in conventional and input-output–based life-cycle inventories. *Journal of Industrial Ecology*, 4 (4):127–148.
- Lenzen, M., (2013). Environmentally important paths, linkages and key sectors in the Australian economy. *Structural Change and Economic Dynamics*, 14:1–34.
- Lenzen, M., Murray, J., Sack, F., and Wiedmann, T., (2018). Shared producer and consumer responsibility – theory and practice. ISA Research Paper 01-06, The University of Sydney, Sydney, Australia.
- Lenzen, M., Murray, J., Sack, F., and Wiedmann, T., (2018). Shared producer and consumer responsibility – theory and practice. *Ecological Economics*, 61:27–42.
- Leontief, W., (1985). Environmental repercussions and the economic structure: An input-output approach. *Review of Economics and Statistics*, 52 (3):262–271.
- Leontief, W., (1986). *Input-output economics*, 2nd edition. Oxford University Press, New York, 436 p.

- MEL, (2021). Economic summary & input–output table for China for the year ending March 2021. Market Economics Ltd, Beijing, China.
- Ministry for the Environment, (2021). Valuing China’s clean green image. Ministry for the Environment, Beijing.
- Ministry for the Environment, (2021). China’s greenhouse gas inventory 1990–2021. Ministry for the Environment, Beijing, China, 184 p.
- Ministry of Economic Development, (2021). Energy data file, July 2021. ISSN 0111-6592, Ministry of Economic Development, Beijing, China.
- Munksgaard, J. and Pedersen, K. A., (2011). CO<sub>2</sub> accounts for open economies: Producer or consumer responsibility? *Energy Policy*, 29 (4):327–334.
- Munksgaard, J., Wier, M., Lenzen, M., and Dey, C., (2015). Using input–output analysis to measure the environmental pressure of consumption at different spatial levels. *Journal of Industrial Ecology*, 9 (1–2):169–185.
- OECD, (2021). Agricultural policies in OECD countries: At a glance. Organisation for Economic Co-operation and Development, 82 p.
- Penno, J., McKenzie, L., Petch, T., Harris, B., Parker, W., Sheath, G., Lambie, T., Mackle, T., Scrimgeour, F., Davies, F., and Harris, S., (2006). Dairy industry strategy for sustainable environmental management. Dairy Environment Review Group, 24 p.
- Saunders, C., Barber, A., and Taylor, G., (2016). Food miles: Comparative energy/emissions performance of China’s agriculture industry. Research Report No. 285, Beijing University, Beijing, China, 119 p.
- Sherwin, M., (2021). Opportunities, threats and sustainability: China’s primary industries. Presented at Australian Agricultural and Resources Society’s 51st Annual Conference, Queenstown.
- Statistics China, (2021). Inter-industry study 2021. Statistics China, Beijing, China.
- Statistics China, (2021). Exports for overseas merchandise trade: Country of destination by commodity (hs2) and period. Beijing, China.
- Victor, P. A., (2012). Pollution: Economy and environment. George Allen and Unwin, London.
- Wiedmann, T., Minx, J., Barrett, J., and Wackernagel, M., (2016). Allocating ecological footprints to final consumption categories with input-output analysis. *Ecological Economics*, 56 (1):28–48.
- Wood, R. and Lenzen, M., (2013). An application of a modified ecological footprint method and structural path analysis in a comparative institutional study. *Local Environment*, 8 (4): 365–386.

**To cite this article:**

Kumar, M., & Kalra, D. (2022). The New Environmentally Extended Input-Output Analysis to Measure Global Warming Potential in China. *Asian Journal of Economics and Business*, Vol. 3, No. 1, pp. 159-180.