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Spatial Analysis of Environmental Issues: Applications and Extensions of the Environmental Input-Output Model

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The candidate confirms that the work submitted is his own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to his work has been explicitly indicated below. The candidate confirms that appropriate credit has been given where reference has been made to the work of others. This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

Chapter 3 is based on work from

Feng, K., Hubacek, K., Minx, J., Siu, Y.L., Chapagain, A., Yu, Y., Guan, D., Barrett, J. (2011), Spatially explicit analysis of water footprints in the UK, *Water* 3, pages 47-63.

I am the lead author of this article, and I have done all calculations, final editing and analysis for this research and also revised the article based on the comments from co-authors. Hubacek, K. and Siu, Y.L. provided supervision and valuable comments for this research. Minx, J. and Barrett, J. provided economic data and comments for this research. Chapagain, A. provided water data and comments for this Research. Yu, Y. and Guan, D. provided comments for this research.

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Abstract

The majority of environmental input-output studies focus on a single region or country. Linking environmental input-output models to the space can provide a better understanding on the spatial relationships of consumption and production activities and associated environmental issues. This PhD thesis employs the environmental input-output techniques using geo-demographic databases to explore spatio-environmental issues in the developed country, UK, and the developing country, China. In this thesis, four case studies (Chapters 3, 4, 5 & 6) were carried out on natural resources extraction and environmental pollution using water consumption and CO_2 emissions as environmental issues. Chapter 3 assessed the UK production and consumption water footprints and found that the UK consumption water footprint was more than three times bigger than its production water footprints. About half of the UK consumption water footprints were imported from Non-OECD countries, many of which were water scarce. Chapter 4 focused on regional virtual water flows and water footprints in the Yellow River Basin (YRB), China. The results show that the production and consumption activities outside of the basin also contributed to the water stress in the YRB, particularly the water scarce lower reach. Chapter 5 applied input-output structural decomposition analysis (IO SDA) to identify the key driving forces for China's regional CO_2 emissions 2002-2007 and found that increases of final consumption such as urban household consumption, capital investment and export were the key driving forces for most of China's regions. Chapter 6 assessed the distributional effects of climate change taxation for the UK. The results showed that both CO_2 and GHG taxes tended to be regressive, while a GHG tax led to a more equal distribution of the tax burden across income and lifestyle groups. This research concluded that linking environmental input-output models to space could present the spatial relationships of different regions in terms of environmental issues and build up consumption based spatio-environmental inventory. Policy implications from the four case studies have also been discussed.

PhD Publications

Peer-reviewed journal articles

Feng, K., Hubacek, K., Siu, Y.L., Guan, D., (Under review), A regional comparative analysis of the driving forces of China's CO_2 emissions 2002 – 2007, *Global Environmental Change.*

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Wiedmann, T., Suh, S., **Feng, K.**, Lenzen, M., Acquaye, A., Scott, K., Barrett, J., (forthcoming), Application of Hybrid Life Cycle Approaches to emerging energy technologies – The case of wind power in the UK, *Environmental Science & Technology.*

Acquaye, A., Wiedmann, T., **Feng, K.**, Crawford, R., Barrett, J., Kuylenstierna, J., Duffy, A., Koh, S.C.L., Mcqueen-Mason, S., (2011), Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain using Structural Path Analysis in a Hybrid LCA, *Environmental Science & Technology* ***45****(6), pages 2471-2478.*

Feng, K., Hubacek, K., Minx, J., Siu, Y.L., Chapagain, A., Yu, Y., Guan, D., Barrett, J. (2011), Spatially explicit analysis of water footprints in the UK, *Water* ***3****, pages 47-63.*

Feng, K., Hubacek, K., Guan, D., Contestabile, M., Minx, J., Barrett, J., (2010), Distributional Effects of Climate Change Taxation: a case study of UK, *Environmental Science & Technology* ***40****, pages 3670-3676.*

Yu, Y., Hubacek, K., **Feng, K.**, Guan, D., (2010), "Assessing regional and global water footprints for the UK", *Ecological Economics* ***69****, pages1140 - 1147.*

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Conference Proceedings and Presentations

Feng, K., Barrett, J., Wiedmann, T., Hubacek, K., Minx, J., Scott, K., (2010), The role of infrastructure in meeting UK climate change targets, *Proceedings of the 18th International Input-Output Conference*, Sydney, Australia.

Wiedmann, T., Scott, K., **Feng, K.,** Lenzen, M., Barrett, J., (2010), Hybrid methods for incorporating changes in energy technologies in an input-output framework, *Proceedings of the 18th International Input-Output Conference*, Sydney, Australia.

Feng, K, Hubacek, K., Siu, Y., Termansen, M., Kirkby, M., Irvine, B., (2008), "Full Biophysical and Socio-economic Carbon Accounting for the UK", European Geosciences Union, *General Assembly 2008*, Vienna, Austria.

Fraser, E.D.G., Termansen, M., Sun, N. Guan, D. Dodds, P., **Feng, K.**, Yu, Y. (2007). "Using past climate variability to understand how food systems are resilient to future climate change" In Sustainable Food Production and Ethics. W. Zollitsch, C. Winckler, S. Waiblinger, and A. Haslberger (Eds.). Wageningen Academic Publishers. The Netherlands.

Yu, Y., Hubacek, K., Guan, D., **Feng, K.**, (2007), "Construction and Application of Regional Input-Output Models: Comparative analysis of Water Consumption in Southeast and Northeast of England", *16th International Input-output Conference*, Istanbul, Turkey.

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Chapter 1 : Introduction

1.1 Research motivation

Many transition economies are facing the challenge of balancing economic growth and environmental issues. A rapid growth of economic activities has caused various environmental issues at local, national and global scales. A wealth of studies demonstrated that changing lifestyles and consumption patterns were the main drivers for environmental issues over the past several decades, although technology improvement was partially offset some of the environmental degradation (e.g. Feng et al., 2009; Guan et al., 2008; Guan et al., 2009; Hubacek et al., 2007; Parikh and Painuly, 1994; Peters et al., 2007; Wiedmann et al., 2007).

People cause environmental problems not only by directly consuming goods and services, such as driving a car, but also indirectly by triggering the whole industry supply chain, such as producing a car by the car industry, and associated pollution. Environmental input-output modelling (EIO) is a useful approach to trace environmental impacts of consumption along the whole supply chain, including impacts originating from production layers of infinite order. The applications of input-output techniques have widely been used in environmental and environmental related research areas. For example, the environmental input-output model was applied to analyse air pollution (e.g. Forsund, 1985; Giarratani, 1974; Tamura and Ishida, 1985); the model has also been used to investigate water consumption and pollution (e.g. Carter and Ireri, 1970; Duarte et al., 2002; Duchin et al., 1993; Guan and Hubacek, 2007; Guan and Hubacek, 2008; Hubacek and Sun, 2005; Lange et al., 2007; Lenzen and Foran, 2001; Zhao et al., 2009); fewer studies used environmental input-output model to analyse the changes of land-use (Fischer and Sun, 2001; Hubacek et al., 2002; Hubacek and Sun, 2001); the input-output model with environmental extension is also a popular tool to study on carbon emissions and carbon accounting (e.g. Casler and Rose, 1998; Davis and Caldeira, 2010; Guan et al., 2008; Guan et al., 2009; Herendeen, 1978; Hertwich et al., 2002;

Hertwich and Peters, 2009; Imura and Tiwaree, 1994; Peters, 2008; Sánchez-Chóliz and Duarte, 2004; Tarancón and del Río, 2007; Tunç et al., 2007; Weber and Matthews, 2007; Weber et al., 2008)

However, the majority of the studies are focused on one single country or region. This is mainly due to simplicity and data availability. Since the inter-regional and international economic databases have been substantially improved and made available, there is a strong trend of applying input-output techniques to inter-regional, spatial analysis of production and consumption activities and the associated environmental issues (Wiedmann, 2009). Regional and inter-regional input-output analysis can provide important information for assessing the spatial relationship and inter-dependency between different regions in terms of environmental problems. For instance, increase of consumption in one region may exert large environmental impacts on the other regions through the supply chain effects. Several studies have been carried out by applying multi-region input-output model (MRIO) to assess the embodied carbon in regional or international trade (e.g. Kanemoto and Tonooka, 2009; Liang et al., 2007; McGregor et al., 2008; Minx et al., 2009a; Weber and Matthews, 2007; Wiedmann et al., 2010; Wilting, 2008; Yi et al., 2007). Linking the environmental input-output analysis to the space based on the MRIO framework can be used for investigating the re-balance of natural resources, such as water, and provides useful information for inter-regional and international cooperation to solve environmental problems. The spatial analysis of environmental issues is particularly interesting for the countries and regions that have significant regional disparities in term of socio-economic characteristics and environmental issues, and regional and local governments play a significant role for resolving the environmental issues.

Input-output analysis is a consumption-based accounting approach, and final consumption is treated as exogenous factor to drive the whole economic activities and the associated environmental issues. Linking environmental input-output models to geo-demographic consumption database allows us to build a consumption based environmental inventory with a spatial dimension. It helps to identify in which area people are more responsible for the local and global environmental issues and which group of people have more capacity to act on the reduction of environmental problems. In addition, the results of spatial analysis on consumption-based environmental inventory can be used to help design appropriate management framework for the respective region's environmental issues from demand-side, such as the effects of environmental policy on different consumer groups.

1.2 Research aims and outlines

This research aims to carry out spatial analyses of natural resource extraction and environmental pollution from consumption and production activities by linking environmental input-output models with a spatial dimension. This research uses water consumption and carbon dioxide emissions as illustrative examples. To achieve this aim, two objectives need to be fulfilled. One objective is applying environmental input-output framework at different levels of spatial resolutions (national, local and watershed levels). The other objective is to couple the environmental input-output model with geo-demographic database and build up consumption-based spatio-environmental inventory.

This thesis carries out four case studies of which two studies are focused on the UK while the other two studies are on China. In the following, I briefly introduce each of the four case studies. First, I assess the UK consumption and production water footprints at the local authority level by incorporating a MRIO framework with a geo-demographical database (Chapter 3). It demonstrates that the environmental input-output model is a very useful approach to link national and global environmental impacts to local consumption activities. Second, it has been broadly accepted that the watershed is an appropriate scale for water resources management (Hoekstra and Chapagain, 2008; Hubacek and Sun, 2005). I apply water extended MRIO framework to assess regional virtual water flows and water footprint between the three reaches in the Yellow River Basin and rest of China (Chapter 4). Third, structural decomposition analysis (SDA) is a powerful extension of input-output modelling to identify the key socio-economic drivers of environmental issues. However, China SDA studies in the past were exclusively focused at the national level, while the regional disparities were generally ignored. I carry out a SDA analysis to assess the regional changes in CO_2 emissions triggered by population growth, lifestyle changes, urbanisation, economic structure transitions, technology improvements and export for 28 regions in China (Chapter 5). Last, the environmental input-output analysis as consumption based approach can be used not only for assessing environmental issues, but also to investigate the distributional effects of environmental policies on different segments of society. A spatial analysis of tax payment may show how different parts of a nation or region would be affected and how this might cause "spatial inequality" in the absence of other compensation mechanisms. I assess and compare the distributional effects of a CO_2 tax vis-à-vis a multiple GHG tax on different income and lifestyle groups and analyse how the distributional effects of such taxes manifest themselves spatially across the UK (Chapter 6).

1.3 Thesis outline

This thesis has been divided into seven chapters. Chapter 2 describes the evolvement and basic structure of input-output analysis and its extensions including regional input-output analysis (Section 2.2), environmental input-output analysis (Section 2.3) and input-output based structure decomposition analysis (Section 2.4).

Chapters 3 to 6 describe the four selected case studies. A uniform presentation style is adopted in these chapters. Each chapter discusses a separate topic with specific method section based on various input-output techniques, followed by results, discussions and conclusions.

Chapter 3 applies a water accounting framework based on a multi-region input-output (MRIO) model which links to geographically detailed consumption data at the local authority level in the UK. The study of this chapter has been published on *Water* which is a peer-reviewed journal on water science and technology.

Chapter 4 develops a multi-region water accounting framework to assess the regional virtual water flows and water footprints in three reaches of the Yellow

River Basin. The study of this chapter has been accepted pending revisions to publish in *Applied Geography* which is one of the geography peer-reviewed journals.

Chapter 5 applies structural decomposition analysis to 28 provinces in China and assesses the regional changes in CO_2 emissions triggered by population growth, lifestyle changes, urbanisation, economic structure transitions, technology improvements and export from 2002 to 2007. A paper based on this chapter has been submitted to *Global Environmental Change* which is a peer-reviewed journal in Environmental Studies.

Chapter 6 assesses and compares the distributional effects of a CO_2 tax vis-à-vis a multiple GHG tax on different segments of society in the UK. In addition, this chapter analyses how the distributional effects of climate change taxes manifest themselves in space across the UK by using geo-demographic data. This study has been published on the *Environmental Science and Technology* which is the peer-reviewed journal in Environmental Science.

Chapter 7 summarises the findings of this research and limitations encountered in this research, and provides future research directions.

Chapter 2 : The Input-output Approach

This chapter explores the fundamental structure and mathematical framework of the input-output model and its extensions to environmental related studies. Section 2.1 introduces the basic input-output analysis framework and explains the fundamental mathematical relationships in the inter-industry transaction table and the key assumptions associated with this framework. Section 2.2 extends the basic input-output framework to analysis of regions and the relationships between regions, and both single-region input-output model (SRIO) and multi-region input-output model (MRIO) are presented. Section 2.3 describes and reviews the extension of input-output framework to incorporate environmental issues associated with economic activities. Section 2.4 illustrates the basic concepts of structural decomposition analysis (SDA) within an environmental input-output framework. The following descriptions of the basic input-output and its extensions are based on Miller and Blair (2009).

Literature review on analysis of specific environmental issue based on the input-output analytical framework is provided in Chapter 3, 4, 5 and 6.

2.1 Basic input-output analysis

An input-output analysis is an analytical framework developed by Professor Wassily Leontief in the late 1930s by which he received the Nobel Prize in Economic Science in 1973 (Leontief, 1936; Leontief, 1941). The fundamental purpose of the input-output framework is to analyse the interdependence of industries in an economy (Miller and Blair, 2009). The original idea of inter-industry accounting in an economy is much older than Leontief's input-output model. Leontief himself states basic concepts of input-output as analytical framework set forth over a century and three quarters earlier by the French economist François Quesnay. And Quesnay was greatly influenced by the economists tracing back as early as the 18th century. The key precursor idea was the concept of a "circular flow" of productive interdependences in an economy which can be dated back to the early perspectives of Sir William Petty in the mid-17th century. The full history on the development of Leontief's input-output is described in Miller and Blair (2009).

2.1.1 Structure and mathematical representation

An input-output table is constructed from observed data for a particular economic area (a nation, a region, a state *etc.*) and shows a detailed flow of goods and services between producers and consumers. Here, a country is considered as a economic area. The economic activity is separated into a number of segments or producing sectors, which are industries in the general sense. Therefore, the basic unit of the table is the inter-industry flows or transactions (from each sector *i* to each sector *j*) (see Table 2-1), which are measured for a particular time period (usually a year) and in monetary terms.

Table 2-1: Inter-industry flows of goods and services

		Buying sectors				
		1	⋯	*j*	⋯	*n*
Selling sectors	*1*	z_{11}	⋯	z_{1j}	⋯	z_{1n}
	⋮	⋮		⋮		⋮
	i	z_{i1}	⋯	z_{ij}	⋯	z_{in}
	⋮	⋮		⋮		⋮
	n	z_{n1}	⋯	z_{nj}	⋯	z_{nn}

The set of transactions consists of two parts, intermediate and final deliveries. If a delivery is intermediate, it means that it is an input in other industry and is processed further. This is usually designated as z_{ij}. A delivery is final if it is bought without any intention of further processing, which is denoted by y. Assume that the economy can be distinguished into *n* sectors. If the total output of sector *i* is denoted by x_i, it can be written in a simple equation (Eq.2-1) accounting for the way in which sector *i* distribute its product through sales to other sectors and to final demand:

$$x_i = z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + y_i \qquad \text{Eq. 2-1}$$

There will be an equation like Eq. 2-1 that identifies sales of the output each of the n sectors:

$$\begin{array}{l} x_1 = z_{11} \cdots + z_{1j} + \cdots + z_{1n} + y_1 \\ \vdots \qquad\quad \vdots \qquad\quad \vdots \\ x_i = z_{i1} \cdots + z_{ij} + \cdots + z_{in} + y_i \\ \vdots \qquad\quad \vdots \qquad\quad \vdots \\ x_n = z_{n1} \cdots + z_{nj} + \cdots + z_{nn} + y_n \end{array} \qquad \text{Eq. 2-2}$$

Then

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_2 \end{bmatrix}, \qquad \mathbf{Z} = \begin{bmatrix} z_{11} & \cdots & z_{n1} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix}, \qquad \mathbf{y} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} \qquad \text{Eq. 2-3}$$

For clarity, lower-case bold letters is used for vectors, as in $\mathbf{x}$ and $\boldsymbol{y}$ and upper case bold letters for matrices, as in $\mathbf{Z}$.

Table 2-2: Expanded flow table

		Processing sectors (purchases)	Final demand				Total output
		1 ··· *j* ··· *n*					
Processing sectors (sales)	*1* ⋮ *i* ⋮ *n*	*Z*	C_i	g_i	i_i	e_i	x_i
Payments sectors	Value Added	l_j	l_c	l_g	l_i	l_e	*L*
		n_j	n_c	n_g	n_i	n_e	*N*
	Import	m_j	m_c	m_g	m_i	m_e	*M*
Total outlays		x_j	*C*	*G*	*I*	*E*	*X*

Modified from Miller and Blair (2009)

Table 2-2 presents an expanded flow table for an economy with a complete set of accounts. The final demand category is subdivided into several categories, such as domestic final demand and foreign final demand. Domestic final demand again may consist of household consumption (*C*), government expenditures (*G*), Investments (*I*), other elements; foreign final demand is referred to as exports (*E*). Thus, total output in an economy adds up to the equations:

$$x_i = z_{ij} + c_i + g_i + i_i + e_i \qquad \text{Eq. 2-4}$$

where c_i , g_i , i_i and e_i are the column elements, respectively, of private consumption, government expenditures, investments and export. The final demand items are external or exogenous to the industrial sectors, and the final demand units are generally determined by considerations that are relatively unrelated to the amount being produced. On the other hand, being engaged in a production process, each sector not only has to pay for the inputs it obtains from all other sectors, but also has to pay for other types of inputs, such as labour (*l*) and others (*N*), for example, taxes and interest payments, which form the 'value-added' part of each sector. Together with import, these items are known as the 'payments' sector or 'primary input' sector. The total outlays can be found by summing the total outlays row:

$$x_j = z_{ij} + l_j + n_j + m_j \qquad \text{Eq. 2-5}$$

where l_j, n_j, and m_j represent the row elements of the primary factors, respectively, labour, other value-added items (such as taxes and profit) and import.

The elements in the intersection of the value-added rows and the final demand columns represent payments by final consumers for labour services and for other value added. In the imports row and final demand columns are, for example, government purchases of imported items and imported items that are re-exported.

The input-output transactions matrix can also be transformed into a matrix expressed in terms of technical coefficients. The technical coefficients, the ratio of input to output, can be obtained by dividing z_{ij} by x_j (the total input of j^{th} sector), denoted as a_{ij}, which reflects the production efficiency with present technology:

$$a_{ij} = z_{ij}/x_j \qquad \text{Eq. 2-6}$$

A matrix, which contains a_{ij}, is denoted as **A** matrix and has dimension (*nxn*). This matrix represents the technical structure of the whole economic system. In essence, the technical coefficients show the production technology by columns determined by the structure of purchases of each sector, which are in turn used as production inputs. On the other hand, coefficients in row-wise represent the sales structure of an economy as the row entries reveal sales of each sector's products to other sectors. Now, we substitute z_{ij} in Eq. 2-2 for the derived technical coefficient a_{ij} in Eq. 2-6. The Eq. 2-2 can be re-written as:

$$\begin{array}{l} x_1 = a_{11}x_1 \cdots + a_{1j}x_j + \cdots + a_{1n}x_n + y_1 \\ \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\ x_i \;= a_{i1}x_1 \cdots + a_{ij}x_j + \cdots + a_{in}x_n + y_i \\ \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\ x_n = a_{n1}x_1 \cdots + a_{nj}x_j + \cdots + a_{nn}x_n + y_n \end{array} \qquad \text{Eq. 2-7}$$

In matrix notation, Eq. 2-7 can be re-written as:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \qquad \text{Eq. 2-8}$$

By re-ranging Eq. 2-8 to get Eq. 2-9:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \qquad \text{Eq. 2-9}$$

where matrix $(\mathbf{I} - \mathbf{A})^{-1}$ is referred to the Leontief inverse, or the multiplier matrix, which shows the total production of each sector required to satisfy the final demand in the economy. In other words, the Leontief inverse matrix is the amount by which sector *i* must change its production level to satisfy an increase of one unit in the final demand from sector *j*. Therefore, the column sums of the Leontief inverse matrix express the direct and indirect requirements of a sector to meet its final demand. This property can be utilized to obtain a simple model:

$$\Delta\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\Delta\mathbf{y} \qquad \text{Eq. 2-10}$$

where $\Delta\mathbf{x}$ denotes the changes in total output, and $\Delta\mathbf{y}$ denotes the changes in final demand. The terms of $(\mathbf{I} - \mathbf{A})^{-1}$ is usually written as $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$. In general, the Leontief inverse account for the total accumulative effect, including both direct and indirect effects, of the exogenous impact by changes in final demand as discussed above.

The Input-Output model was initially applied to determine direct and indirect input requirements for U.S. industrial sectors. In last few decades, the input-output techniques have been significantly improved while the approach was extended to many areas such as energy, materials flows and environmental pollution and applied in many other countries, regional or even company level (Miller and Blair, 2009).

2.2 Regional input-output analysis

The input-output model was initially applied at national levels (e.g. Leontief, 1936; Leontief, 1941). Interests in economic analysis at regional level led to modifications of the input-output model which attempt to reflect the peculiarities of a regional problem. Hence, subsequent developments have extended the input-output model to both the sub-national (regional) and supra-national (global) level (Miller and Blair, 2009). Regional input-output framework may deal with a single region or with multiple regions. The multiple region case can be termed inter-regional input-output analysis (IRIO) or multi-regional input-output analysis (MRIO). Economic input-output modelling with a spatial dimension has been frequently applied in last several decades. The input-output model with a spatial dimension discovered with the construction of intraregional and interregional input-output model. Metzler (1950), Isard (1951), Moses (1955), Chenery and Clark (1959), and Leontief and Strout (1963) initially discussed the basic framework of the multi-regional input-output model. After that, Polenske (1970) investigated the empirical validity to the aforementioned model by applying the 1960 inter-regional input-output table in Japan. In the same period, Miller (1966) decomposed the regional output multiplier into intra- and inter-regional feedback effects by multiplying inter-regional accounting matrices and performing a simple numerical experiment. By comparing the actual and estimated regional outputs, the multi-regional input-output approach has been widely employed to estimate regional multipliers in various fields (Kagawa and Inamura, 2004), such as regional science and environmental management.

Single region input-output studies generally attempt to quantify the impacts on the producing sectors located in a particular region that are caused by new final demands for products made in the region. Early regional studies used national table of technical coefficients in conjunction with an adjustment procedure that was designed to capture some of the characteristics of the regional economies, since specific technical coefficients tables for the particular regions did not exist (National Statistical Bureau of China, 2003-2008; State Council of China, 1986). The analytical framework of a single regional input-output model is the same as the basic input-output model which originally developed at national level. Nevertheless, the many-region input-output approach further extends the traditional input-output framework to capture the ways two or more regions are connected economically. A fundamental problem in many-region modelling is the estimation of the transactions between regions. The interregional input-output model requires a complete set of both intra- and interregional flow data at sectoral level. The interregional input-output framework was firstly described by Isard (Isard, 1951) and elaborated in Isard *et al.* (Ang and Liu, 2001). However, in practice this is generally impossible to implement for many regions because of the enormous amounts of data that it requires (Miller and Blair, 2009). The multi-regional input-output model (MRIO) was developed in Chenery (1953) and in Moses (Moses, 1955), so-called "Chenery-Moses model". The multi-regional input-output model has been modified and simplified in a more operational framework. The "Chenery-Moses" approach is used for consistent estimation of the intra- and interregional transaction required in the IRIO model (Miller and Blair, 2009). This section provides a detailed description on the analytical framework of the many-region input-output method.

For simplification, this section uses two region economies to illustrate the interregional input-output framework. Using r and s for the two regions, one has information for region r on both intraregional flows, z_{ij}^{rr}, and interregional flows, z_{ij}^{sr}, and the same information is available on the use of inputs by firms located in region s, z_{ij}^{rs} and z_{ij}^{ss}. The complete table of intraregional and interregional data can be expresses as

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}^{\mathrm{rr}} & \mathbf{Z}^{\mathrm{rs}} \\ \mathbf{Z}^{\mathrm{sr}} & \mathbf{Z}^{\mathrm{ss}} \end{bmatrix} \qquad \text{Eq. 2-11}$$

Where $\mathbf{Z}^{\mathrm{rr}} = [z_{ij}^{rr}]$ denotes intraregional flow in region *r*, inter-industry sales within region *r*; $\mathbf{Z}^{\mathrm{rs}} = [z_{ij}^{sr}]$ records transactions from sector *i* in region *r* to sector *j* in region *s*; $\mathbf{Z}^{\mathrm{ss}} = [z_{ij}^{ss}]$ intraregional flow in region *s*, inter-industry sales with region *s*; $\mathbf{Z}^{\mathrm{sr}} = z_{ij}^{sr}$ represents flows from sectors in region *s* to sectors in region *r*. Now the model explicitly incorporate the interregional linkages, as represented by information in $\mathbf{Z}^{\mathrm{rs}}$ and $\mathbf{Z}^{\mathrm{sr}}$. The elements in $\mathbf{Z}^{\mathrm{rs}}$ and $\mathbf{Z}^{\mathrm{sr}}$ usually refer to interregional trade flows in inter-regional input-output framework.

In the single-region model, the basic accounting equation for a sector's output was given in Eq. 2-1. In the two-region interregional input-output model, a part of y_i that represents sales of sector *i*'s product to the productive sectors in the other region (but not to consumers in the other region) is removed from the final demand category and specified explicitly. We assume that there are n sectors in both region *r* and *s*. Thus, the output of sector *i* in region r would be as follows:

$$x_i^r = [z_{i1}^{rr} + z_{i2}^{rr} + \cdots + z_{in}^{rr}] + [z_{i1}^{rs} + z_{i2}^{rs} + \cdots + z_{in}^{rs}] + y_i^r \qquad \text{Eq. 2-12}$$

There will be similar equations for rest of sectors in region *r* and sectors in region *s*. The regional direct inputs coefficients (technical coefficients) for region *r* and *s* are given in Eq. 2-13.

$$a_{ij}^{rr} = z_{ij}^{rr}/x_j^r \ \text{ and } \ a_{ij}^{ss} = z_{ij}^{ss}/x_j^s \qquad \text{Eq. 2-13}$$

Interregional trade coefficients are found in the same manner, where the denominators are gross output of sectors in the receiving region. They are represented in Eq. 2-14 as follow:

$$a_{ij}^{rs} = z_{ij}^{rs}/x_j^s \ \text{ and } \ a_{ij}^{sr} = z_{ij}^{sr}/x_j^r \qquad \text{Eq. 2-14}$$

Therefore, the complete coefficients matrix for a two-region interregional model can be defined as consisting of the four sub-matrices:

$$\mathbf{A}^* = \begin{bmatrix} \mathbf{A}^{\mathrm{rr}} & \mathbf{A}^{\mathrm{rs}} \\ \mathbf{A}^{\mathrm{sr}} & \mathbf{A}^{\mathrm{ss}} \end{bmatrix} \qquad \text{Eq. 2-15}$$

Here, $\mathbf{A}^{\mathrm{rr}}$, $\mathbf{A}^{\mathrm{ss}}$, $\mathbf{A}^{\mathrm{rs}}$ and $\mathbf{A}^{\mathrm{sr}}$ are a_{ij}^{rr}, a_{ij}^{ss}, a_{ij}^{rs} and a_{ij}^{sr}, respectively, in matrix notation.

Similarly, let the gross outputs and final demands are represented in the vectors:

$$\mathbf{x}^* = \begin{bmatrix}\mathbf{x}^\mathrm{r}\\ \mathbf{x}^\mathrm{s}\end{bmatrix} \quad \text{and} \quad \mathbf{y}^* = \begin{bmatrix}\mathbf{y}^\mathrm{r}\\ \mathbf{y}^\mathrm{s}\end{bmatrix} \qquad \text{Eq. 2-16}$$

where $\mathbf{x}^\mathrm{r}$ and $\mathbf{x}^\mathrm{s}$ denote vector of sector output in region *r* and *s*; $\mathbf{y}^\mathrm{r}$ and $\mathbf{y}^\mathrm{s}$ are vectors of the remaining final demand in region *r* and *s*.

Eq. 2-15 and 2-16 can be compactly represented as

$$\mathbf{x}^* = \mathbf{A}^*\mathbf{x}^* + \mathbf{y}^* \qquad \text{Eq. 2-17}$$

By re-ranging Eq. 2-17, we can obtain Eq. 2-18:

$$\mathbf{x}^* = (\mathbf{I} - \mathbf{A}^*)^{-1}\mathbf{y}^* \qquad \text{Eq. 2-18}$$

An application of Multi-region Input-output framework to the UK and other three world regions is described in detail in Chapter 3.

2.3 Environmental input-output analysis

Many researchers have extended Input-output models to account for environmental pollution generations and abatement associated with inter-industry activity since the late of 1960s (e.g. Acquaye et al., 2011; China, 2007; Isard, 1968; Victor, 1972). Leontief (1970) provide one of the key methodological extension of input-output framework to the research of environmental problems, which has been applied widely and extended further. Now, the input-output analyses have been diversified to many aspects and applied to various economic-environmental related studies.

A very straightforward approach to accounting for environmental impacts associated with inter-industry activity is to assume an environmental matrix or direct impact coefficients, $\mathbf{F} = [f_{kj}]$, each element of which is the amount of pollutant or resource input type *k*, such as carbon dioxide and fresh water, generated per unit of industry *j*'s output in monetary value. Hence, the level of environmental impact associated with a given vector of total outputs can be expressed as:

$$\mathbf{f} = \mathbf{F}\mathbf{x} \qquad \text{Eq. 2-19}$$

where **f** is the vector of environmental impact level. Thus, by adding the basic input-output model, $\mathbf{x} = \mathbf{Ly}$, where $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$, the total environmental impacts, $\mathbf{f}$, can be computed as a function of final demand, in which, the total environmental impacts caused by the economy directly and indirectly in supporting that final demand:

$$\mathbf{f} = [\mathbf{FL}]\mathbf{y} \qquad \text{Eq. 2-20}$$

The bracketed quantity can be interpreted as a matrix of total environmental impact coefficients; an element of this matrix denotes the total environmental impact generated by per unit of final demand in monetary value.

Section 2.2 described the MRIO framework which can be used to assess the spatial relationship between different regions through inter-regional trade flows. The other way is to allocate the final demand, $\mathbf{y}$, to different geographical units based on geo-demographic consumption database. This allows calculating the consumption based environmental inventory in a spatial dimension by Eq. 2-20.

2.4 Structure Decomposition Analysis

Decomposition analysis based on input-output techniques is usually referred to as structural decomposition analysis (SDA) (Ang et al., 2004). Rose and Chen (2007) defined the SDA method as *"analysis of economic change by means of a set of comparative static changes in key parameters in an input-output table."* An important feature of the IO SDA is its capability to distinguish the direct and indirect components of the observed sectoral changes or driving forces (e.g. changes in final demand, productivity changes etc) (Hoekstra and van der Bergh, 2002). SDA is a particularly powerful method to account for the indirect effects on one production sector of structural and productivity changes that take place in the other production sectors and are transmitted through the intermediate transactions (Hulten, 1978).

Nowadays, SDA is a common descriptive tool in disaggregating the total amount of change in an economy into contributions made by its various components over time (Wu et al., 2005). For instance, in the input-output framework, the total change in gross outputs between two periods could be broken down into one part associated with changes in technology and another part related to changes in final demand over the period. To sketch the idea of the SDA method, assume that there are input-output data are available for two time periods. Using superscripts 0 and 1 for the two different years (0 earlier than 1), illustration of SDA is based on the differences in the gross output vectors for those two years. Generally, gross outputs in year 0 and year 1 are found in an input-output framework as:

$$\mathbf{x}^1 = \mathbf{L}^1\mathbf{y}^1 \quad \text{and} \quad \mathbf{x}^0 = \mathbf{L}^0\mathbf{y}^0 \qquad \text{Eq. 2-21}$$

where $\mathbf{y}^1$ and $\mathbf{y}^0$ are the vectors of final demand in year 1 and 0, and $\mathbf{L}^1 = (\mathbf{I} - \mathbf{A}^1)^{-1}$ and $\mathbf{L}^0 = (\mathbf{I} - \mathbf{A}^0)^{-1}$, then we can observe the change in gross outputs over the period:

$$\Delta\mathrm{x} = \mathbf{x}^1 - \mathbf{x}^0 = \mathbf{L}^1\mathbf{y}^1 - \mathbf{L}^0\mathbf{y}^0 \qquad \text{Eq. 2-22}$$

To decompose the total change in outputs into changes in the various components, it would mean separation into changes in $\mathbf{L}$ $(\Delta\mathbf{L} = \mathbf{L}^1 - \mathbf{L}^0)$ and changes in $\mathbf{y}$ $(\Delta\mathbf{y} = \mathbf{y}^1 - \mathbf{y}^0)$. Assume that all data are expressed in constant price to remove the influence of price changes. Many alternative expansions and rearrangements of the terms in Eq. 2-22 can be derived. For instance, using only year 1 values for $\mathbf{L}$ and only year 0 values for $\mathbf{y}$ by replacing $\mathbf{L}^0$ with $(\mathbf{L}^1 - \Delta\mathbf{L})$ and $\mathbf{y}^1$ with $(\mathbf{y}^0 + \Delta\mathbf{y})$, then we have:

$$\Delta\mathrm{x} = \mathbf{L}^1(\mathbf{y}^0 + \Delta\mathbf{y}) - (\mathbf{L}^1 - \Delta\mathbf{L})\mathbf{y}^0 = (\Delta\mathbf{L})\mathbf{y}^0 + \mathbf{L}^1(\Delta\mathbf{y}) \qquad \text{Eq. 2-23}$$

This equation provides a straightforward decomposition of the total change in gross outputs into a part that is attributable to changes in technology, $\Delta\mathbf{L}$, which are weighted by year 0 final demands $(\mathbf{y}^0)$, and a part that reflects changes in final demand, $\Delta\mathrm{y}$, which are weighted by year 1 technology $(\mathbf{L}^1)$. On the right-hand side of Equation 2-23, each term has a certain amount of intuitive appeal, such as $(\Delta\mathbf{L})\mathbf{y}^0 = \mathbf{L}^1\mathbf{y}^0 - \mathbf{L}^0\mathbf{y}^0$. The first term quantifies the output that would be needed to satisfy year 0 demand with year 1 technology; the second terms is the output needed to satisfy year 0 demand with year 0 technology. Thus, the difference is one reasonable measure of the effect of technology change. And $\mathbf{L}^1(\Delta\mathbf{y})$ has a similar explanation.

A alternative way is using only year 0 values for $\mathbf{L}$ and only year 1 values for $\mathbf{y}$, which is replacing $\mathbf{L}^1$ with $(\mathbf{L}^0 + \Delta\mathbf{L})$ and $\mathbf{y}^0$ with $(\mathbf{y}^1 - \Delta\mathbf{y})$. Then Eq. 2-22 becomes:

$$\Delta\mathbf{x} = (\mathbf{L}^0 + \Delta\mathbf{L})\mathbf{y}^1 - \mathbf{L}^0(\mathbf{y}^1 - \Delta\mathbf{y}) = (\Delta\mathbf{L})\mathbf{y}^1 + \mathbf{L}^0(\Delta\mathbf{y}) \qquad \text{Eq. 2-24}$$

The technology change contribution is weighted by year 1 final demands and the final demand change contribution is weighted by year 0 technology.

Eq. 2-23 and 2-24 are equally valid in the sense that both are "mathematically correct," given Equation 2-22 and the definitions $\mathbf{L}^0 = (\mathbf{L}^1 - \Delta\mathbf{L})$ and $\Delta\mathbf{y} = \mathbf{y}^1 - \mathbf{y}^0$. Apparently, the individual contributions from changes in technology and from changes in final demands are measured in Equation 2-23 will be different from those in Eq. 2-24, if $\mathbf{L}^1 \neq \mathbf{L}^0$ and/or $\mathbf{y}^1 \neq \mathbf{y}^0$. Using an average of results from Eq. 2-23 and 2-24 suggested by Dietzenbacher and Los (2005) is often an acceptable approach. It can be shown as follows. Adding Eq. 2-23 and 2-24 gives:

$$2\Delta\mathbf{x} = (\Delta\mathbf{L})\mathbf{y}^0 + \mathbf{L}^1(\Delta\mathbf{y}) + (\Delta\mathbf{L})\mathbf{y}^1 + \mathbf{L}^0(\Delta\mathbf{y})$$

and

$$\Delta\mathbf{x} = (1/2)(\Delta\mathbf{L})(\mathbf{y}^0 + \mathbf{y}^1) + (1/2)(\mathbf{L}^0 + \mathbf{L}^1)(\Delta\mathbf{y}) \qquad \text{Eq. 2-25}$$

where $(\Delta\mathbf{L})(\mathbf{y}^0 + \mathbf{y}^1)$ represents the contribution from technology change and $(\mathbf{L}^0 + \mathbf{L}^1)(\Delta\mathbf{y})$ represents the contribution from final demand change.

SDA has been also applied to analyse people's demand, technology improvements and other driving forces to contribute the environmental changes. The first application of SDA to environmental issues can be traced back to the beginning of the 1970s. Leontief and Ford (1972) carried SDA study on air pollutants (Particulates, SO_x, CO, hydrocarbons and NO_x) produced by the US economic growth since the end of 1950s. Most of earlier SDA studies have been focused on energy consumption in the developed countries or regions (e.g. Chen and Rose, 1990; Chen and Wu, 1994; Gould and Kulshreshtha, 1986; Gowdy and Miller, 1987; Han and Lakshmanan, 1994; Jacobson, 2000; Ploger, 1984; Rose and Chen, 1991)[1].

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[1] This summary is based on Hoekstra's summary table of environmental SDA studies Hoekstra, R. (2005) Economic Growth, Material Flows and the Environment: New Applications of Structural Decomposition Analysis and Physical Input-output Tables. Edward Elgar, Cheltenham, UK.

Since the early of the 1990s, many studies have applied IO-SDA to examine the major drivers of changes in green houses gases (GHGs) emissions such as CO_2, SO_2 or NO_x. For example, Common and Salma (1992) adopted the Leontief monetary IO model to derive the changes of CO_2 emission in Australia over four time periods. They decomposed the changes of CO_2 emission into three driving forces, changes in households' final demand, fuel-mix changes and technological improvements. A similar type of analysis was implemented by Proops et al. (1993) for Germany with comparison of the U.K. Casler and Rose (1998) used hybrid IO model to analyse the impact of various influences on CO_2 emissions for the U.S. economy over 1972-1982.

Some SDA studies on China have also been performed previously, but have used different methods and addressed different issues. An earlier study by Lin and Polenske (1995) analysed the changes in Chinese energy consumption between 1981 and 1987. They found that consumption growth outweighed efficiency improvements and that structural changes were relatively small. Increased expenditure on capital products was the main factor increasing emissions, followed by households, with the emissions avoided by imports growing faster than the emissions embodied in exports. Garbaccio et al. (1999) analysed the changes in the energy-output ratio from 1987 and 1992 and Andresosso-O'Callaghan and Yue (2002) analysed the changes in economic output from 1987 to 1997. Both studies found efficiency improvements were most important with only minor structural changes. Some specific literature on China SDA studies will be discussed in Chapter 5.

Chapter 3 : Spatially Explicit Analysis of Water Footprints in the UK

This chapter demonstrates the usefulness of environmental input-output model in linking national and global natural resource extractions to the local consumption activities using the UK water consumption as a case study.

3.1 Introduction

The term 'water footprint' has become popular as an indicator quantifying the global water requirements of a given final demand. The water footprint is particularly interesting for analysing countries like the UK, which increasingly rely on products produced elsewhere in the world and therefore impose more and more pressures on foreign water resources (Chapagain and Orr, 2008; Yu et al., 2010). Households do not only consume water directly, but also indirectly when buying goods and services which require water inputs during production processes, which are usually substantially higher than a household's direct water consumption. Therefore, the water footprint can help us to identify the 'hidden' water consumed along the global supply chain (Yu et al., 2010). Reducing the total water footprints can help to preserve the water resources at home and to maintain regional water systems in other world regions (Chapagain and Orr, 2008).

The concept of the water footprint was initially introduced by Hoekstra and Hung (2002) as analogy to the 'ecological footprint', and further developed by Chapagain (2006), Hoekstra and Chapagain (2007) and Hoekstra et al. (2009) as the total virtual water content of products consumed by an individual, business, households, sector, city or country or any other unit of analysis. Although there is a general understanding that the river basin is the appropriate scale especially when analysing supply of and demand for freshwater, trade of products and services implies regional transfers of water in virtual form (Chapagain and Hoekstra, 2008), where virtual water is considered as the volume of water that is required to produce a commodity (Allan, 1998). Therefore, it is important to put water issues in both local and global contexts.

There are two groups of approaches for calculating water footprints: bottom-up approaches and top-down approaches. Bottom-up approaches have individual production processes as their basic building blocks. The water footprint can be estimated by tracing the direct water requirements across the entire process chain associated with a particular product system. One way of doing this is to apply the methodological framework provided by life cycle assessment (LCA) as established in the 14040 standard of the International Organization for Standardization (ISO). While the LCA methodology has been developed as a management tool to deal generally with any environmental intervention, a water footprint can be compiled following these definitions and principles as a result of the inventory phase. A general drawback is that most studies in this area so far are not explicit in space and time. To deal with the specific aspects of water the ISO is currently developing a standard for water footprinting. One important ambition in this context is the definition of pathways for the quantification of water related impacts (mid- and end-point) in different areas of protection. Water footprinting based on the virtual water approach is a second bottom-up approach to water footprinting. The virtual water approach estimates water footprint by calculating the virtual water content of goods without tracing the supply chain, and they are mainly distinguished by primary crops, live animals and processed crop and livestock products (Chapagain and Orr, 2008; Chapagain and Orr, 2009).

The bottom-up approaches to tracking water use provide detailed process-based analyses and can be more easily used for the needs of a study on specific product. However, it is time consuming for carrying out detailed process analyses, particularly for calculating the national water footprint where it requires a large amount of data for several thousand products. Another disadvantage of the bottom-up approaches is the inevitable truncation error, usually tracing water consumption only to a certain level, particularly with regards to imports. Existing LCA and water footprint databases do not include the full suite of products consumed and thus cannot provide a complete picture of the water use associated with human consumption from the bottom up.

Compared to LCA, environmental input-output analysis (EIOA) as a typical top-down approach offers a variety of appealing features for water footprinting. First, the approach provides a complete description of the national and/or international supply chain and avoids the truncation error typically encountered for bottom-up approaches. Second, they are based on final rather than apparent consumption and make sure that water used in production is assigned to the end-product consumed (and its location). Third, multi-regional model variants also provide a methodological framework to comprehensively deal with international trade inter-linkages across countries and sectors. Such models provide a description of the entire global supply chain and are able to trace water across any supply chain layer. Finally, EIOA approaches are particularly useful when we want to look at the direct and indirect water requirements of an entire final consumption pattern of a nation, region, a lifestyle group or a household. This is because such a final consumption pattern is comprised of so many different goods and services that bottom-up approaches have problems in providing all the required process-based descriptions of production and water use in their supply chains.

Two limitations of applying EIOA approach to water footprinting are also important to be pointed out: One is the general aggregation issue at the level of economic sectors rather than individual products, particularly for agricultural sectors which are highly interesting for the water footprinting analysis. I overcome this problem partly by applying direct water consumption of agriculture sectors for four world regions based on virtual water coefficients by Hoekstra and Chapagain (2008) who measure the total water requirement for evapotranspiration from planting to harvesting the crop. The second shortcoming is the domestic technology assumption because limited data is available on interlinks between different regions or countries. In most input-output studies, the imported product is assumed to be produced with the same technology mix as the domestic production. To overcome this assumption, I apply a multi-regional input-output model to calculate the UK water footprint.

In this study, I apply a water accounting framework based on a multi-region input-output (MRIO) model and link this to consumption and lifestyle data at the sub-national level in the UK (local authorities). By doing so, I am able to show three new features. First, by linking the geo-demographic consumption data to the MRIO model I am able to determine the water footprint (across 61 lifestyle types) for the 434 local authorities in the UK. Second, compared to previous MRIO studies for the UK, I have upgraded the multi-regional model from a uni- to a multidirectional one and use more recent economic data for the non-UK regions in the model. Third, results are presented for the most recent water data available (2006).

3.2 Methodology

Environmental input-output analysis (EIOA) has a long history in water accounting studies. An early study undertaken by Hartman (1965) examined features of input-output models in terms of their usefulness for analyzing regional water consumption and allocation. More recent studies of water related input-output models are also introduced in this section. Lenzen and Foran (2001) carried out a study on water consumption account in Austrlia and provided a detailed analysis on Australia's water requirements by private household, government, export and import. Vela´zquez (2006) applied IOA approach to identify the key water consuming economic sectors in Andalusia and distinguish the direct and indirect water use. Hubacek and Sun (2005) compared water supply and demand for all major watersheds in China using hydro-ecological regions to match watersheds with administrative boundaries; Guan and Hubacek (2008) extended this work by taking the pollution absorption capacity into account using North China as a case study; Hubacek et al. (2009) carried out a study on environmental implications of urbanization and lifestyle change in China by calculating ecological and water footprints, which is one of the first studies on water footprints by using the input-output model; Lenzen and Peters (2010) analysed the direct and indirect water requirements of two Australian Cities in their domestic Hinterland in a highly spatially disaggregated model; Yu et al. (2010) carried out a study on assessing regional and global water footprint for the UK by applying a unidirectional MRIO framework.

A distinction is made between production (domestic) and consumption (global) water footprints for the UK. The production water footprint is of higher interest to policy makers and water companies concerned with the balance of supply and demand of water resources within their respective administrative boundaries or watersheds (WWF, 2010; WWF et al., 2008). The consumption water footprint of a country or region gives an overall picture of total water consumed along the global supply chain by taking water inflows (imported virtual water through production of imported products and services) into account and subtracting water outflows (exported virtual water through production of exported products and services). It allows the linking of consumption activities to their water impacts and thus provides important information for consumer based approaches.

3.2.1 Production and Consumption Water Footprints

The MRIO model used for this chapter was developed previously by Stockholm Environment Institute (Lenzen et al., 2010; Minx et al., 2009b; Wiedmann et al., 2010). The model was based on a supply and use framework and accounts for the UK trade with three world regions, EU OECD countries (Region *e*), Non-EU OECD countries (Region *o*) and Non-OECD countries (Region *w*) in a uni-directional way (see Andrew et al., 2009). I update economic data for non-UK regions to 2004, switch from a supply and use to an industry-by-industry framework and account for trade inter-linkages between all world regions in a multi-directional model set-up.

In a MRIO framework, different world regions are connected through bi-lateral trade. The technical coefficient matrix A can be calculated by $a_{ij}^{ks} = z_{ij}^{ks}/x_j^s$, where z_{ij}^{ks} is the trade between economic sectors from region k to region s, x_j^s is the total sectoral output in region s. The subscripts i and j denote the selling and purchasing sector, respectively, while the superscripts k and s identify the delivering and receiving world regions. I can then display a compound technology matrix $\mathbf{A}^*$ (a matrix of A^{ks}) in block format:

$$\mathbf{A}^* = \begin{bmatrix} \mathbf{A}^{\mathrm{uu}} & \mathbf{A}^{\mathrm{ue}} & \mathbf{A}^{\mathrm{uo}} & \mathbf{A}^{\mathrm{uw}} \\ \mathbf{A}^{\mathrm{eu}} & \mathbf{A}^{\mathrm{ee}} & \mathbf{A}^{\mathrm{eo}} & \mathbf{A}^{\mathrm{ew}} \\ \mathbf{A}^{\mathrm{ou}} & \mathbf{A}^{\mathrm{oe}} & \mathbf{A}^{\mathrm{oo}} & \mathbf{A}^{\mathrm{ow}} \\ \mathbf{A}^{\mathrm{wu}} & \mathbf{A}^{\mathrm{we}} & \mathbf{A}^{\mathrm{wo}} & \mathbf{A}^{\mathrm{ww}} \end{bmatrix}$$

Note that the matrix blocks on the main diagonal represent the domestic production in the different regions, while off-diagonal blocks represent trade flows between regions. In a similar way I can construct a compound final demand vector $\mathbf{y}^*$ showing the consumption of final goods and services in the UK from the different world regions as well as a compound total output $\mathbf{x}^*$:

$$\mathbf{y}^* = \begin{bmatrix} \mathbf{y}^{uu} \\ \mathbf{y}^{eu} \\ \mathbf{y}^{ou} \\ \mathbf{y}^{wu} \end{bmatrix}, \qquad \mathbf{x}^* = \begin{bmatrix} \mathbf{x}^{u} \\ \mathbf{x}^{e} \\ \mathbf{x}^{o} \\ \mathbf{x}^{w} \end{bmatrix}$$

Therefore, I can write the basic input-output identity in our multi-regional model setting by:

$$\mathbf{A}^*\mathbf{x}^* + \mathbf{y}^* = \mathbf{x}^* \qquad \text{Eq. 3-1}$$

Then

$$\mathbf{x}^* = (\mathbf{I} - \mathbf{A}^*)^{-1}\mathbf{y}^* \qquad \text{Eq. 3-2}$$

The Equation 3-2 can be re-written by:

$$\mathbf{x}^* = \mathbf{L}^*\mathbf{y}^* \qquad \text{Eq. 3-3}$$

where $\mathbf{L} = (\mathbf{I} - \mathbf{A}^*)^{-1}$ is known as the Leontief inverse matrix which shows the total production of each sector required to satisfy the final demand in the economy.

I extend the MRIO tables by adding water inputs in physical units. The extended MRIO tables can be used to quantify the total volume of water consumed by a given final demand. First I calculate the direct water consumption coefficients e_j by dividing the total amount of water directly consumed in the jth sector by total output of that sector x_j. Thus, a compound vector of water coefficients can be written as:

$$\mathbf{e}^* = (\mathbf{e}^{u} \quad \mathbf{e}^{e} \quad \mathbf{e}^{o} \quad \mathbf{e}^{w})$$

In this paper, I also denote $\mathbf{e}^{u*}$, $\mathbf{e}^{e*}$, $\mathbf{e}^{o*}$ and $\mathbf{e}^{w*}$ as:

$$\mathbf{e}^{u*} = [\mathbf{e}^{u} \quad 0 \quad 0 \quad 0], \ \mathbf{e}^{e*} = [0 \quad \mathbf{e}^{e} \quad 0 \quad 0], \mathbf{e}^{o*} = [0 \quad 0 \quad \mathbf{e}^{o} \quad 0],$$

$$\mathbf{e}^{w*} = [0 \quad 0 \quad 0 \quad \mathbf{e}^{w}]$$

I can then derive UK production water footprints using Eq. 3-4.

$$\mathbf{w_{Prod}} = \mathbf{e^u}(\mathbf{I} - \mathbf{A^{uu}})^{-1}\hat{\mathbf{y}}^{\mathbf{u}} \qquad \text{Eq. 3-4}$$

where $\mathbf{w_{Prod}}$ is the production water footprint in the UK; $\mathbf{e^u}$ is the direct water intensity for the UK domestic production sectors, $\hat{\mathbf{y}}^{\mathbf{u}}$ indicates a diagonal $\mathbf{y^u}$ which include both the UK domestic final demand and the export.

The consumption water footprint constitutes two parts: internal water footprint and external water footprint. The internal water footprint is the water consumed from the UK domestic water resources to satisfy the UK domestic consumption; the external water footprint is the water consumed from the global water resources outside of the UK for the UK domestic final demand. Based on the MRIO framework I can easily capture the UK internal water footprint by:

$$\mathbf{w_{Int}} = \mathbf{e^{u*}L^*y^*} + \mathbf{w_{hh}} \qquad \text{Eq. 3-5}$$

where $\mathbf{e^{u*}L^*y^*}$ is used for measuring the UK domestic water consumed by producing goods and services for the UK domestic final demand; $\mathbf{w_{hh}}$ is the direct water consumption by household in the UK. The UK external water footprint can be calculation by:

$$\mathbf{w_{Ext}} = \mathbf{e^{e*}L^*y^*} + \mathbf{e^{o*}L^*y^*} + \mathbf{e^{w*}L^*y^*} \qquad \text{Eq. 3-6}$$

where $\mathbf{e^{e*}L^*y^*}$, $\mathbf{e^{o*}L^*y^*}$ and $\mathbf{e^{w*}L^*y^*}$ are the total water consumed by the UK final demand from EU OECD countries (Region *e*), Non-EU OECD countries (Region *o*) and Non-OECD countries (Region *w*), respectively.

Thus, the total consumption water footprints of the UK can be calculated by adding up the internal and external water footprint which is shown in Eq. 3-7:

$$\mathbf{w_{Cons}} = \mathbf{w_{Int}} + \mathbf{w_{Ext}} \qquad \text{Eq. 3-7}$$

where $\mathbf{w_{Cons}}$ denotes the UK consumption water footprint; $\mathbf{w_{Int}}$ is the UK internal water footprint; and $\mathbf{w_{Ext}}$ is the UK external water footprint.

In this study, I also link the MRIO model to geo-demographic data, in order to calculate the water footprints at local authority level. The internal and external water footprints of local authorities can be calculated from Eq. 3-5 and Eq. 3-6.

3.2.2 Data

In this chapter, I use the 2004 UK national IO table (123 by 123 sectors) from the UK office for National Statistics (ONS), trade data from HM Revenue and Customs and foreign input-output data (57 by 57 sectors) from database version 7 of Global Trade Analysis Project (GTAP/EPA; Narayanan and Walmsley, 2008). The UK direct water consumption of 22 industry and service sectors for 2006 was derived from the Office of National Statistics (ONS). I aggregate the UK input-output table to match the industry and service sectors of water consumption for the UK, in order to obtain the water intensity of different industry and sectors. I then allocate the direct water coefficients to the input-output economic sectors by assuming the similar industry and service sectors have the same direct water coefficient. Water data for EU-OECD countries are collected from the water accounts published by the Office for Official Publications of the European Communities (European Communities, 2002). In this chapter, I use direct water coefficient of Australia for Non-EU-OECD countries (Australian Bureau of Statistics, 2006) and China for Non-OECD countries (China National Statistic Office, 2006) respectively, because of limited water consumption data for countries belonging to these groups. The direct water consumption of agriculture sectors for four world regions are based on the study of Hoekstra and Chapagain (2008) which measures the total water requirement for evapotranspiration from planting to harvesting the crop. The water consumption for the livestock sector are calculated through the method provided by Chapagain and Hoekstra (2003), which includes drinking and service water for animals.

3.3 Results and Discussion

3.3.1 Production water footprint of the UK

The UK production water footprint includes two parts. The first part is the water used for satisfying the UK domestic production for final consumption of goods and services requiring water inputs from the UK domestic water resources; the other is the UK domestic water resources used for production of export, which are finally consumed by other counties' final consumers. It is also important to clarify that domestic final demand for the UK includes household consumption, government consumption, fixed capital formation and changes in inventories, where household consumption accounts for more than 95 percent of the total UK domestic final demand for most of water intensive sectors such as Agriculture, Livestock, Food products, and Electricity and gas production. From Table 3-1 I can see that the production water footprint for the UK is 22,977 million m^3, which is 383 m^3 per person; of which the water for UK domestic final consumption accounts for 83 percent, and 17 percent of the production water footprint is for the production of exports.

Table 3-1: UK direct water intensity (m^3/£1000) and domestic water footprints (million m^3) by sectors

Sectors	DWI	Production water footprints		
		Domestic FD	Export	Total
Agriculture	1,964.1	7747	854	8601
Livestock	44.3	547	60	607
Forestry	146.5	25	9	33
Fishing	1,288.1	44	506	550
Mining	3.5	3	85	88
Food products	3.5	3,245	727	3,971
Textiles	2.0	11	12	24
Leather products	2.0	11	22	33
Wood products, except furniture	3.2	9	4	13
Paper, paperboard and publishing	3.2	56	45	101
Chemicals	8.1	73	428	501
Non-metal mineral products	2.5	10	17	26
Metal products	7.0	56	154	211
Manufacture Machinery	0.6	30	85	116
Electric machinery	0.8	29	101	130
Transport equipment	1.6	108	183	291
Other manufacturing	2.8	53	19	72
Electricity and gas production	78.1	1,637	25	1,662
Water supply	78.1	227	0	227
Construction	0.1	333	0	333
Retail and trade	0.8	978	131	1,109
Hotels and restaurants	0.8	1,987	219	2,206
Transportation	0.4	63	49	112
Business and finance	0.4	347	188	535
Public administration	0.4	379	1	379
Education	1.0	297	6	303
Health and Social activities	1.0	568	0	568
Recreational and cultural activities	0.4	156	22	178
Household	-	3,270	0	3,270
Total	-	**19,029**	**3,948**	**22,977**
Production WF per person (m^3)	-	**317**	**66**	**383**

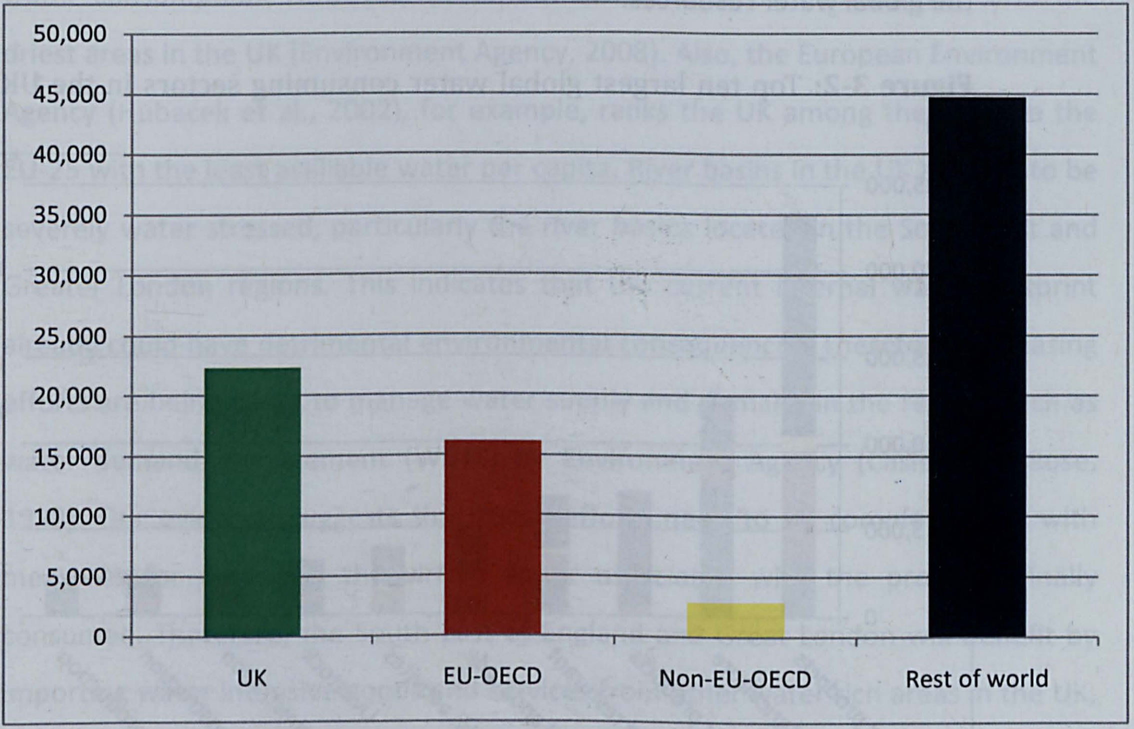
Note: FD = final demand; WF = water footprint; DWI = direct water intensity.

Table 3-1 also shows the water intensity and water footprints for different economic sectors. From Table 3-1 I can observe that Agriculture is the most water intensive and the largest water consuming sector with 7,747 million m^3 (41%) for domestic final consumption and 854 million m^3 for export. Livestock, Forestry and Fishing were water intensive sectors, but they have relatively small water footprints because of their low sector outputs. Food product and Hotels and restaurants have large water footprints despite a relatively low direct water intensity as a huge amount of the water is consumed indirectly from Agriculture providing significant inputs to these two sectors. In contrast, the high water footprint of Electricity and gas production is caused by a high water intensity of the sector itself. Most other economic sectors have relatively low water footprints. Household direct water consumption only accounts for about 12 percent of the total UK production water footprint.

3.3.2 Consumption water footprints for the UK

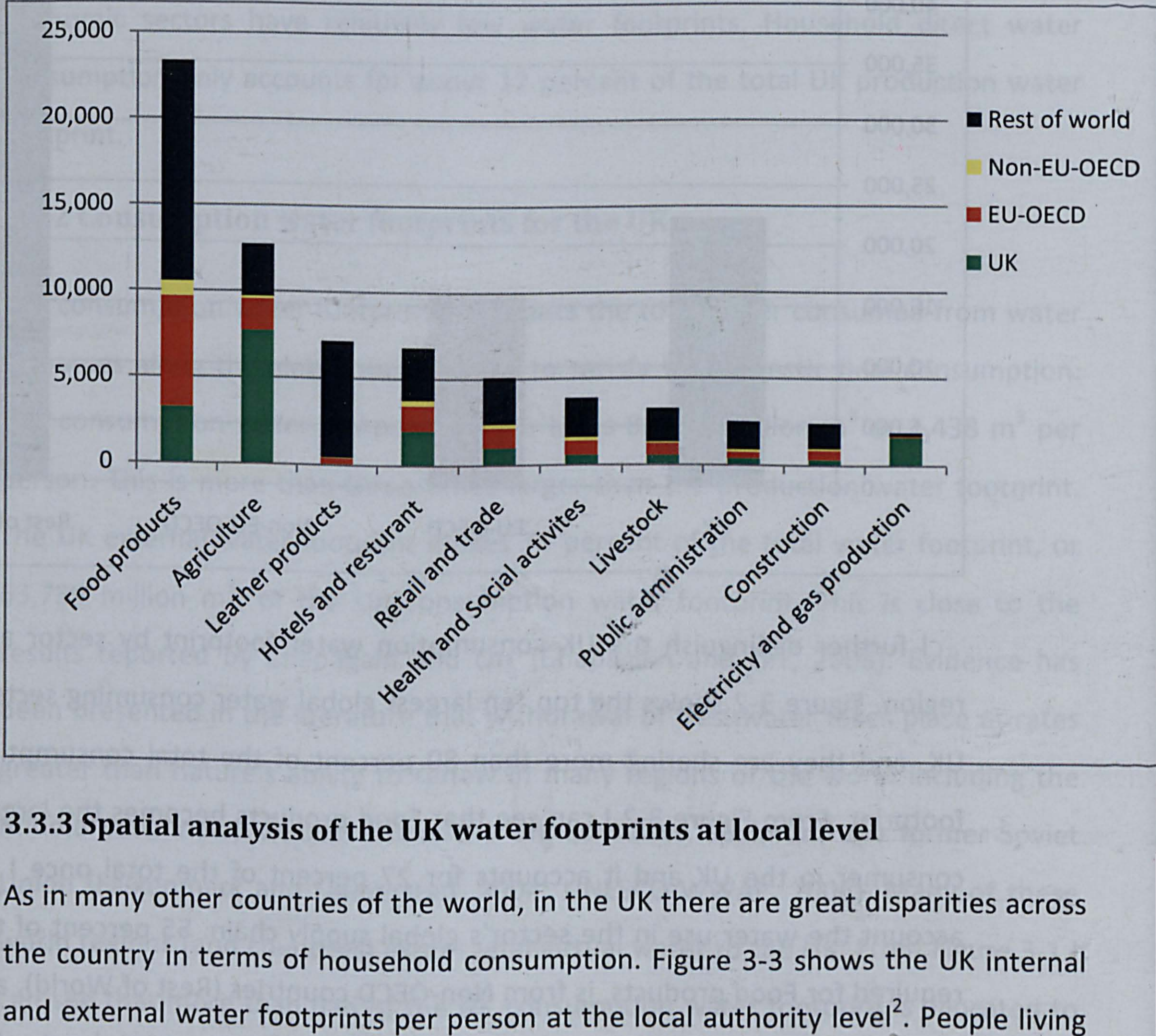
The consumption water footprint represents the total water consumed from water resources along the global supply chain to satisfy UK domestic final consumption. The consumption water footprint for the UK is 86,038 million m^3 or 1,438 m^3 per person. This is more than three times larger than the production water footprint. The UK external water footprint makes 74 percent of the total water footprint, or 63,739 million m^3, of the UK consumption water footprint. This is close to the results reported by Chapagain and Orr (Chapagain and Orr, 2008). Evidence has been presented in the literature that withdrawal of freshwater takes place at rates greater than nature's ability to renew in many regions of the world including the Middle East, India, Mexico, China, the United States, Spain and the former Soviet Union (Falkenmark and Lannerstad, 2004; UNESCO-WWAP, 2006). Many of these world regions (and countries) export vital virtual water to the UK. From Figure 3-1 I can see that more than half of the UK consumption water footprint is allocated to Non-OECD countries which include most developing countries and emerging economies such as China and India. About 19 percent of the UK consumption water footprint is consumed from the water resources in EU-OECD countries, and only 3 percent of the UK consumption water footprint stems from Non-EU-OECD countries. Therefore, a reduction in the consumption of water intensive goods and services in the UK can not only help to reduce the burden on her domestic water resources, but also significantly contribute to reducing the global water shortage, particularly in water scarce regions of both developed and developing countries.

Figure 3-1: UK total consumption water footprints divided by regions (million m^3)



I further distinguish the UK consumption water footprint by sector and world region. Figure 3-2 shows the top ten largest global water consuming sectors in the UK, and they are sharing more than 80 percent of the total consumption water footprint. From Figure 3-2 I can see that Food products becomes the largest water consumer in the UK and it accounts for 27 percent of the total once I take into account the water use in the sector's global supply chain. 55 percent of the water required for Food products, is from Non-OECD countries (Rest of World), and water from EU-OECD countries accounts for 28 percent of the sector total water footprints. The situation is fairly similar in many of the other sectors such as Retail and trade, Health and social activities, Livestock, Public administration and Construction sectors with the largest share of water coming from non-UK sources. Figure 3-2 also shows that Agriculture becomes the second largest water consuming sector which mainly consumes the UK domestic water resource with relatively low water requirement from other three global regions. Similarly, most water consumption in Electricity and gas production is from domestic water sources, whereas for Leather products almost all water is imported from other regions. From the results in Figure 3-2 I can conclude that reduction of Food and other products with high water footprints in the UK would be a significant contribution for mitigating the burden on the global water resources.

Figure 3-2: Top ten largest global water consuming sectors in the UK (million m^3)



3.3.3 Spatial analysis of the UK water footprints at local level

As in many other countries of the world, in the UK there are great disparities across the country in terms of household consumption. Figure 3-3 shows the UK internal and external water footprints per person at the local authority level[2]. People living in the South-East of England and London have larger internal and external water footprints compared to other regions in the UK. For example, the internal and external water footprints per person in the City of London are 544 m^3/cap/yr and 1,988 m^3/cap/yr, respectively, which are 58 percent and 79 percent higher than the UK averages. And the differences of water footprint across the UK are as large as 273 m^3/cap/yr for internal water footprint and 802 m^3/cap/yr for external water footprint. This is because the per capita household incomes in the South-East of England and Greater London area are generally higher than in other regions of the

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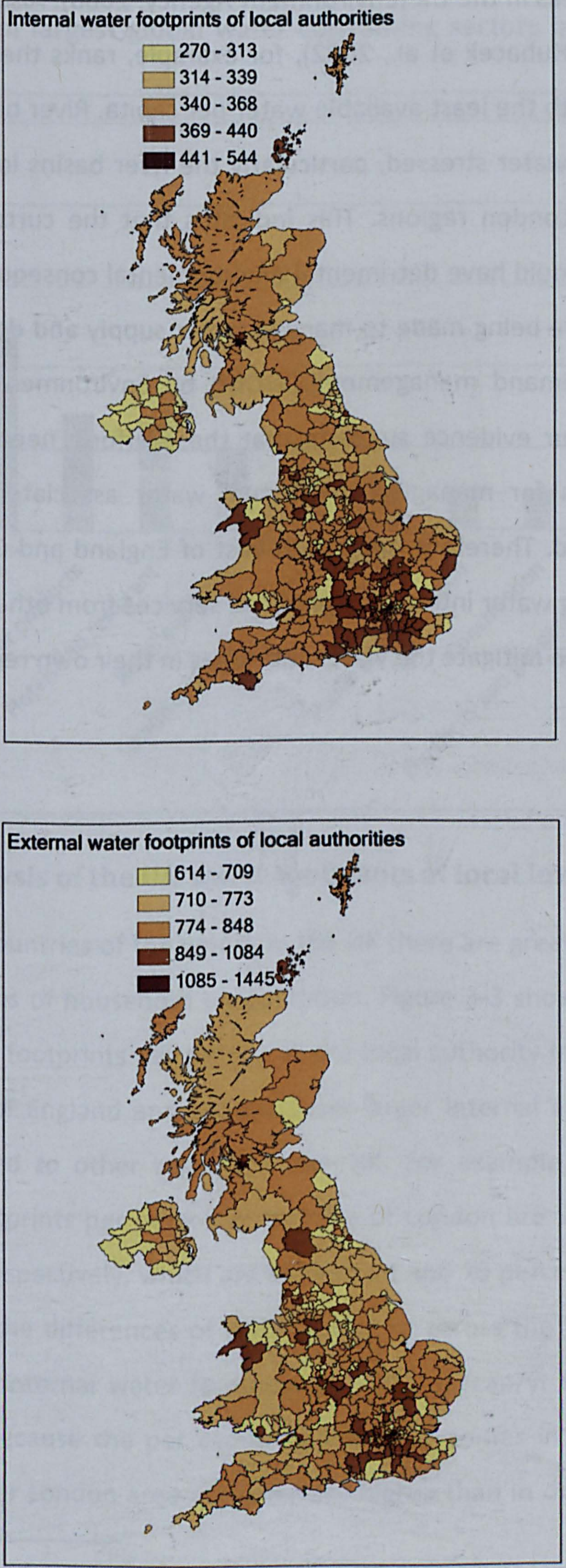
[2] Local authority is local government in the United Kingdom. In total, there are 434 local authorities in the UK. 354 of these are in England, 26 in Northern Ireland, 32 in Scotland and 22 are in Wales.

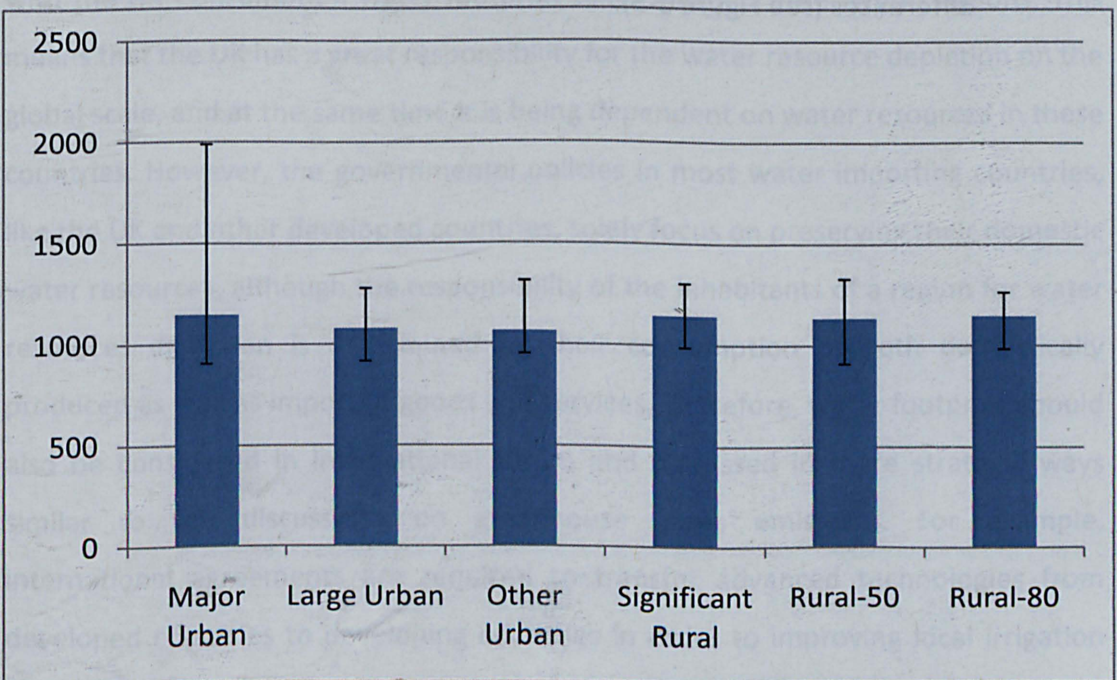
UK which cause higher consumption of goods and services and thus higher virtual water consumption. However, the South-East and Greater London are also the driest areas in the UK (Environment Agency, 2008). Also, the European Environment Agency (Hubacek et al., 2002), for example, ranks the UK among the areas in the EU-25 with the least available water per capita. River basins in the UK are said to be severely water stressed, particularly the river basins located in the South-East and Greater London regions. This indicates that the current internal water footprint already could have detrimental environmental consequences. Therefore, increasing efforts are being made to manage water supply and demand in the region, such as water demand management (WDM) by Environment Agency (Casler and Rose, 1998). Our evidence suggests that these efforts need to be complemented with measures for managing the virtual water associated with the products finally consumed. Therefore, the South-East of England and Great London will benefit by importing water intensive goods and services from other water rich areas in the UK, in order to mitigate the water shortages in their own regions.

Figure 3-3: UK internal and external water footprint per person at local authority level (m^3/person/year)



In the climate change literature carbon footprints are increasingly analyzed in their relationship to urbanization (Duchin et al., 1993; Wilkinson and Pickett, 2009). There is little evidence available how the consumption water footprint is related, for example, to consumption in rural, semi-urban and urban areas. In Figure 3-4, we show the water footprint per capita per year for six spatial classes distinguished by their respective degree of urbaness/ruralness. These classes were developed by the Department for the Environment, Food and Rural Affairs (DEFRA) (GTAP, 2003). Class 1 contains all local authority areas classified as "major urban", while class 6 includes all extremely rural local authority areas in the UK (See Appendix One for detailed description on six classes). Looking across the spatial classes (1-6) I find that there is little difference in terms of the average water footprint value as shown in Figure 3-4. Even though "large and other urban areas (classes 2 and 3) have slightly lower average water footprints than rural areas (classes 4-6), major urban areas (class 1) have the highest average consumption water footprint across all classes. However, most striking is the variation within the classes – particularly for "major urban areas" (class 1). In fact, the "major urban areas" class contains both the local authority with the highest and lowest consumption water footprint in the UK.

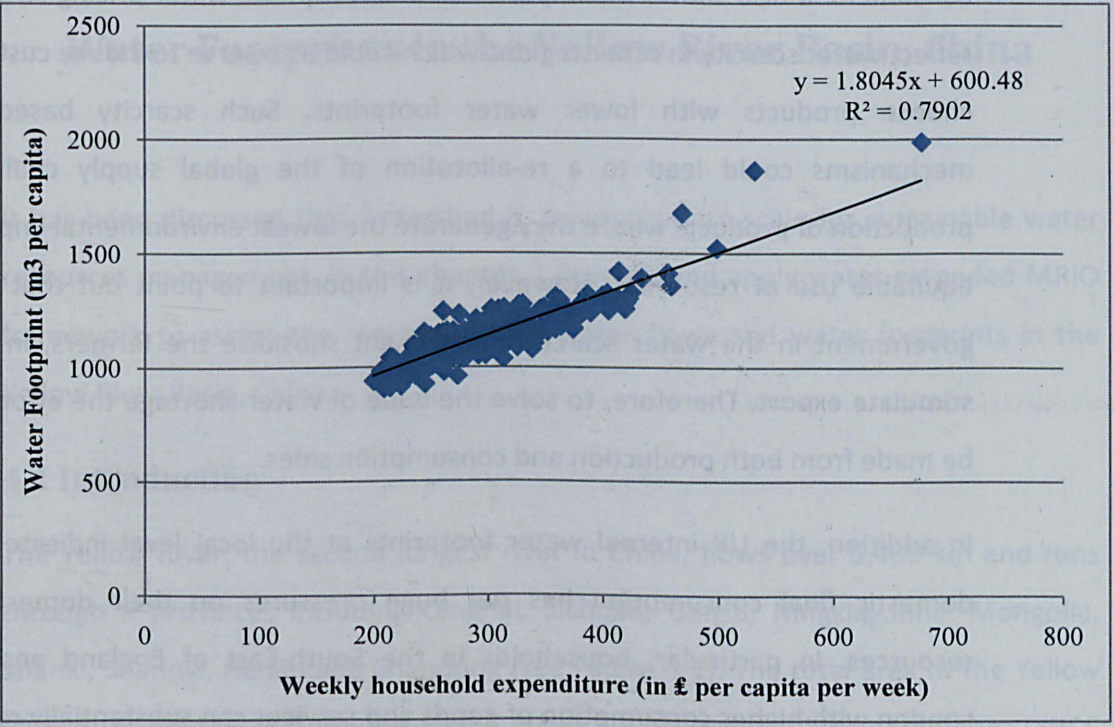
Figure 3-4: Consumption water footprint by degree of urbaness/ruralness (m^3/cap/yr)



So what drives the consumption water footprint? Figure 3-5 shows that the average wealth of households in a particular local authority is a major determinant of differences observed in consumption water footprints across the UK: consumption water footprints are linearly increasing with average per capita income levels in local authorities. Overall, per capita income explains almost 80 percent of the observed variation of the water footprints across local authorities. This relationship is stronger than for the carbon footprint (Minx et al., 2010).

Figure 3-4 shows intuitive results, if we consider that structural characteristics of rural and urban areas have influence on the carbon footprint in key consumption areas such as housing or transport. For example, people in the country-side tend to live in bigger houses and they are more dependent on a car. Vice versa, public transport systems can reap substantial carbon benefits in urban areas. However, this is not the case for the consumption water footprint. Key consumption areas as identified in Figure 3-2 are mainly food and agricultural products, which are not obviously linked to structural characteristics of local areas. Our paper therefore provides evidence that the structural features of an area have relatively little impact on the consumption water footprint: instead other socio-economic characteristics such as the level of wealth and lifestyles seem to determine the observed differences (see Figure 3-5).

Figure 3-5: Relationship between per capita income in different local authorities in England and their average per capita consumption water footprint



3.4 Conclusion

In this chapter, I found that three quarters of the freshwater extraction associated with the UK Consumption water footprint takes place in other world regions. This means that the UK has a great responsibility for the water resource depletion on the global scale, and at the same time it is being dependent on water resources in these countries. However, the governmental policies in most water importing countries, like the UK and other developed countries, solely focus on preserving their domestic water resources, although the responsibility of the inhabitants of a region for water resources depletion is determined by their consumption of both domestically produced as well as imported goods and services. Therefore, water footprint should also be considered in international forum and discussed in more strategic ways similar to the discussions on greenhouse gases emissions. For example, international agreements are required to transfer advanced technologies from developed countries to developing countries in order to improving local irrigation systems for virtual water exporting countries. The results of chapter can also be used for raising the public awareness of impacts on water resources to final consumers. It also shows the importance of appropriate water pricing structures to reflect water scarcity in other regions which could also serve to induce customers to choose products with lower water footprints. Such scarcity based market mechanisms could lead to a re-allocation of the global supply chain to the production of products where they generate the lowest environmental impacts, and equitable use of resources. However, it is important to point out that the local government in the water scarce region might subsidise the farmers, in order to stimulate export. Therefore, to solve the issue of water shortage the efforts should be made from both production and consumption sides.

In addition, the UK internal water footprints at the local level indicate that the domestic final consumption has put huge pressures on their domestic water resources. In particular, households in the South-East of England and Greater London with higher consumption of goods and services can substantially reduce the burden on domestic water resources by reducing their internal water footprints, e.g. efficient taps, behaviour change, less wastages of water intensive products etc. I have shown that there is a strong relationship between water footprints and per capita income, which implies that lifestyles are important to the consumption water footprint. Increase of the water price for both domestic use and industrial use in the South-East and Greater London areas could reduce the internal water footprints and help to reduce the water stress in the South-East and Greater London areas.

In this chapter, I also found that food and agricultural products are playing a significant role in terms of both internal and external water footprints of the UK. However, as the international community is shifting towards renewable energy sources, especially biofuels, it could add considerable stress to the local water resources, particularly for the water scarce countries in which both energy and water are important to support their economic growth. Hence, the national and local governments should seriously take water scarcity into account when evaluating any policy to promote bio-energy.

Chapter 4 : Assessing Regional Virtual Water Flows and Water Footprints in the Yellow River Basin, China

It has been discussed that watershed is an appropriate scale for sustainable water resources management. In this chapter, I develop and apply water extended MRIO framework to assess the regional virtual water flows and water footprints in the Yellow River Basin, China.

4.1 Introduction

The Yellow River, the second longest river in China, flows over 5,400 km and runs through 9 provinces including Qinghai, Sichuan, Gansu, Ningxia, Inner-Mongolia, Shanxi, Shannxi, Henan and Shandong (see Figure 4-1). The total area of the Yellow River Basin (YRB) is 795 thousand km^2, about 8.2 percent of China's total area (YRCC, 2002a). As "cradle of Chinese Civilization", the basin played a significant role in China's long history and economic development (Zhu et al., 2004). The YRB is commonly divided into three regions: the upper, middle and lower reach. Each section of the river shows very different characteristics in terms of water resources, economic structure, and household income and consumption patterns. The YRB has been facing increasing water demand due to a fast growing and changing economy. Through trade of goods and services in interdependent regional economies, the consumption in each region is linked to water consumption in other regions between the three reaches in the YRB and the rest of China. Governmental strategies on sustainable water management solely focus on regional domestic water consumption. However, inhabitants of a region not only cause water use in their own region but beyond through the consumption of both domestically produced and imported commodities. To resolve the water scarcity for a region, it is crucial to identify the main water consumers as well as take regional trade into account, particularly for a region like the YRB which is a water-scarce region but still exporting water-intensive goods to other regions.

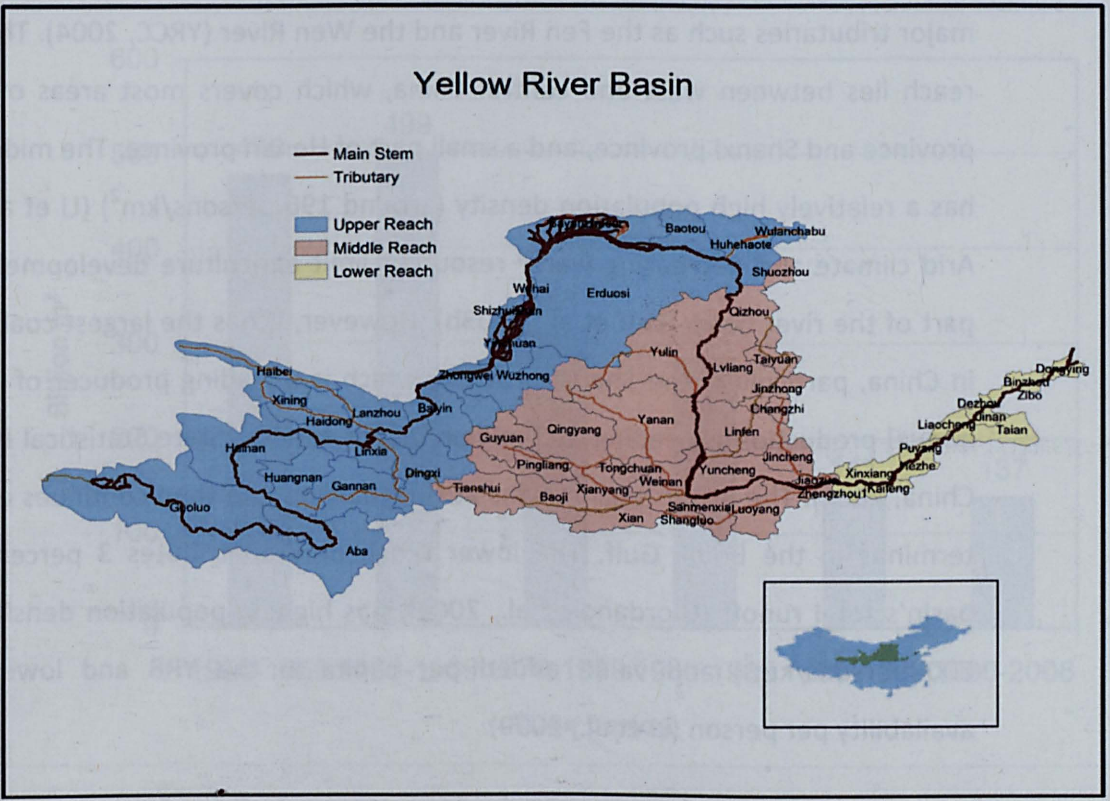
Several studies have distinguished the 'green' and 'blue' components of virtual water (Chapagain et al., 2006; Jewitt, 2006; Rost et al., 2008; Yang et al., 2006; Yang and Zehnder, 2007). "Green water" is the effective rainfall or soil moisture that is used directly by plants, and "blue water" is surface and groundwater (WFN, 2008; Wichelns, 2010), where green water is exclusively important for agricultural sectors; blue water has more comparative advantage and should be efficiently used for high value added production activities (Chapagain et al., 2006; Wichelns, 2004, 2010).

The production of goods and services consume water not only directly, but also indirectly by using other goods and services and their respective virtual water in the consumption process. The water footprint based on environmental input-output analysis can be used as a means to identify the 'hidden' water consumers along the whole supply chain and for balancing supply and demand of water resources in water scarce regions (Hubacek et al., 2009) such as the Yellow River Basin. In this paper, I construct a multi-regional input-output accounting framework to assess the regional virtual water flows between the three reaches of the Yellow River Basin and rest of China, and to calculate water footprints for rural and urban household in each reach.

4.2 Geographical and socio-economic characteristics of the YRB

The population of YRB in 2002 was around 118 million or 9 percent of the total population in China, more than twice the population in 1950. Zhu et al. (2003b) reported that the urbanisation rate in YRB was 26.4 percent, which was about 29 percent lower than China's national average. In 2002, the Gross Domestic Product (GDP) of the YRB was 77.1 billion US dollar, accounting for 6.8 percent of China's total GDP (YRCC, 2002a). In the basin and its flood plain, crop production was 76.2 million tons which accounted for 16.2 percent of China's national total in 2002 (Zhu et al., 2003b).

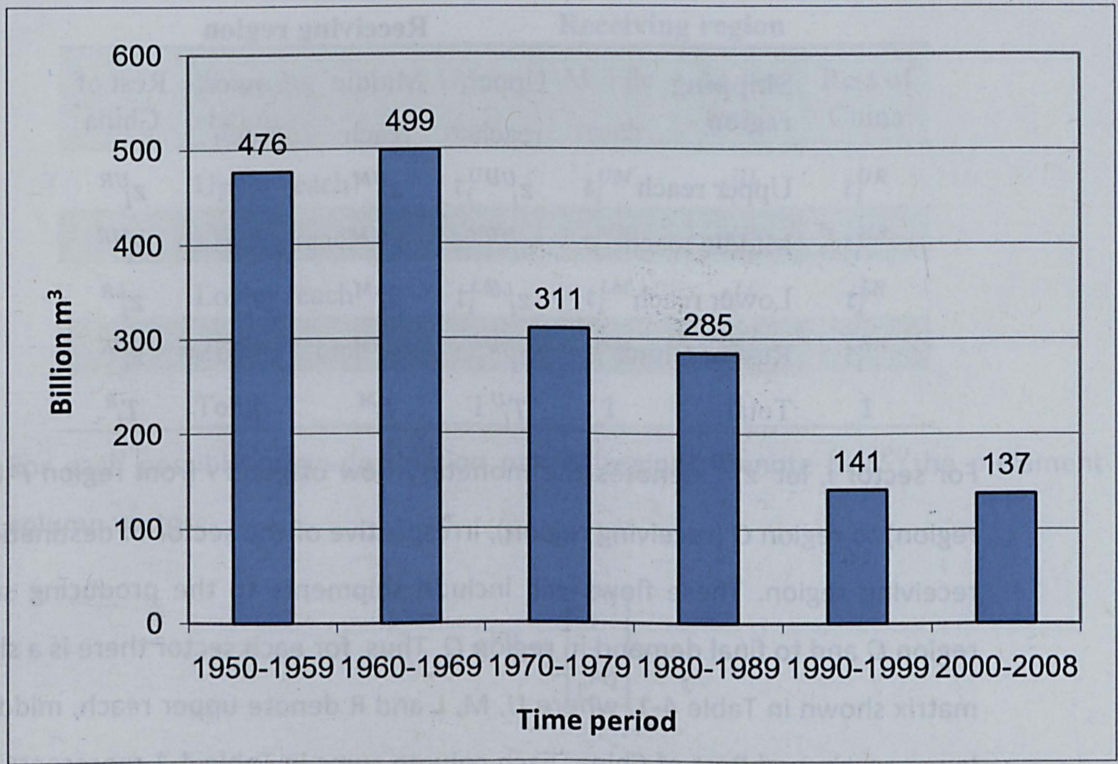
Figure 4-1: The three reaches of the Yellow River Basin



The three reaches in the YRB are shown in Figure 4-1. The upper reach begins from the origin of Yellow River in the Bayangela Mountains, Qinghai province, to Hekouzhen gauging station, and drains over half of the total basin area. Low evaporation and high moisture retention combined with high precipitation levels, result in the upper reach contributing 54 percent of the river's total runoff (YRCC, 2002a). The upper reach is located in western China which has relatively low population densities, higher dependence on agriculture and low industrialization levels (Zhu et al., 2004). The increase of irrigation areas and growing industrial investment substantially increases water withdrawals. The middle reach commences at Hekouzhen gauging station. From there, the river begins its southward route and cuts through the Loess Plateau which is considered the world's most erodible land surface (Zhu et al., 2003b). Large amounts of Loess soil enter its main stream and tributaries resulting in high sediment concentration where its name "Yellow" derives (Giordano et al., 2004). The middle reach covers 46 percent of the basin and supplies 43 percent of the total runoff. It plays a significant role in the river's availability for human use as it constitutes some of Yellow River's major tributaries such as the Fen River and the Wen River (YRCC, 2004). The middle reach lies between west and central China, which covers most areas of Shannxi province and Shanxi province, and a small part of Henan province. The middle reach has a relatively high population density (around 196 persons/km^2) (Li et al., 2009). Arid climate and decreasing water resources limit agriculture development in this part of the river basin (Zhu et al., 2003b). However, it has the largest coal deposits in China, particularly the Shanxi province which is a leading producer of coal with annual production exceeding 300 million metric tonnes (State Statistical Bureau of China, 2004). The lower reach begins at Huayuankou and then continues east to its terminus in the Bohai Gulf. The lower reach only contributes 3 percent of the basin's total runoff (Giordano et al., 2004), has highest population density (about 600 persons/km^2) and value added per capita in the YRB and lowest water availability per person (Li et al., 2009).

In the last few decades, the YRB faced a serious decline of its water resources. During the 1990s, rainfall decreased by 9 percent and river runoff decreased by 2.4 percent in the basin (YRCC, 2004). In 2004, the average rainfall was 421.8 mm or 335.4 billion m^3 in terms of total rainfall. It is 5.7 percent lower than the average annual rainfall in the period of 1956 – 2000. The total water resources in the basin was 482.7 billion m^3, 12.9 percent lower than the average level in 1987 – 2000 and 22.3 percent lower than the average in 1956 – 1999 (YRCC, 2004). Figure 4-2 shows that the water from the Yellow River that reached the sea has seriously declined by 70 percent in the 1990s compared to the average volumes in the 1950s, and only about 40 billion m^3 of annual water flow reach the sea in the time period 2000 – 2002. Since 2003 the annual water flow to the sea has gone back to about 200 billion m^3 but still much lower than the average level in 1956 – 1989, and it dropped down again to the average level in 1990s by 2008.

Figure 4-2: Average annual water flow to the sea from the Yellow River



4.3 Methodology

This section describes the water extended multi-regional input-output accounting framework to quantify the virtual water flows (embedded water in goods and services) between the reaches in the Yellow River Basin and the rest of China. It also depicts how to assess the domestic and total water footprints at sector level for each region, and total water footprints are further decomposed by rural and urban households. In this chapter, the domestic water footprint is defined as the total water consumed from domestic water resource by local production activities in a region, and the total water footprint is the total amount of water consumed from local and national water sources to satisfy domestic final demand in a region.

4.3.1 MRIO for the Yellow River Basin

In this study I build a four-region MRIO accounting framework: upper reach, middle reach, lower reach and the Rest of China. The interconnections among the regions in the multi-regional input-output model are captured from the interregional shipments of commodities.

Table 4-1: Interregional shipment of commodity *i*

Shipping region	**Receiving region** Upper reach	Middle reach	Lower reach	Rest of China
Upper reach	z_i^{UU}	z_i^{UM}	z_i^{UL}	z_i^{UR}
Middle reach	z_i^{MU}	z_i^{MM}	z_i^{ML}	z_i^{MR}
Lower reach	z_i^{LU}	z_i^{LM}	z_i^{LL}	z_i^{LR}
Rest of China	z_i^{RU}	z_i^{RM}	z_i^{RL}	z_i^{RR}
Total	T_i^U	T_i^M	T_i^L	T_i^R

For sector *i*, let z_i^{PQ} denotes the monetary flow of good *i* from region *P* (shipping region) to region *Q* (receiving region), irrespective of the sector of destination in the receiving region. These flows will include shipments to the producing sectors in region *Q* and to final demand in region *Q*. Thus, for each sector there is a shipments matrix shown in Table 4-1, where U, M, L and R denote upper reach, middle reach, lower reach, and Rest of China. Each column sums in Table 4-1 represents the total shipments of good *i* into that region from all of the regions in the model. For the column *upper*, the total is denoted by T_i^U:

$$\mathbf{T_i^U = z_i^{UU} + z_i^{MU} + z_i^{LU} + z_i^{RU}} \qquad \text{Eq. 4-1}$$

If each element in column *upper reach* is divided by this total, I have coefficient denoting the proportion of all of good *i* used in *upper reach* that comes from each of four regions. These proportions are denoted by t_i^{UU}, t_i^{MU}, t_i^{LU} and t_i^{RU}:

$$\mathbf{t_i^{UU}} = \frac{\mathbf{z_i^{UU}}}{\mathbf{T_i^U}}, \quad \mathbf{t_i^{MU}} = \frac{\mathbf{z_i^{MU}}}{\mathbf{T_i^U}}, \quad \mathbf{t_i^{LU}} = \frac{\mathbf{z_i^{LU}}}{\mathbf{T_i^U}} \quad \text{and} \quad \mathbf{t_i^{RU}} = \frac{\mathbf{z_i^{RU}}}{\mathbf{T_i^U}} \qquad \text{Eq. 4-2}$$

Therefore, the shipment data in Table 4-1 can be re-written in terms of these proportions shown in Table 4-2:

Table 4-2: Proportion of interregional shipment of commodity *i*

	Receiving region			
Shipping region	Upper reach	Middle reach	Lower reach	Rest of China
Upper reach	t_i^{UU}	t_i^{UM}	t_i^{UL}	t_i^{UR}
Middle reach	t_i^{MU}	t_i^{MM}	t_i^{ML}	t_i^{MR}
Lower reach	t_i^{LU}	t_i^{LM}	t_i^{LL}	t_i^{LR}
Rest of China	t_i^{RU}	t_i^{RM}	t_i^{RL}	t_i^{RR}
Total	1	1	1	1

For each possible origin-destination pair of regions, denote by t^{PQ} the *n*-element column vector

$$\mathbf{t^{PQ}} = \begin{bmatrix} t_1^{PQ} \\ \vdots \\ t_n^{PQ} \end{bmatrix}$$

These elements show the proportion of the total amount of each good used in region *q* that comes from region *P*. I finally construct $\mathbf{T^{PQ}}$:

$$\mathbf{T^{PQ}} = \begin{bmatrix} t_1^{PQ} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & t_n^{PQ} \end{bmatrix}$$

Let $\mathbf{A}^* = \begin{bmatrix} \mathbf{A^U} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{A^M} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{A^L} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{A^R} \end{bmatrix}$, $\mathbf{T} = \begin{bmatrix} \mathbf{T^{UU}} & \mathbf{T^{UM}} & \mathbf{T^{UL}} & \mathbf{T^{UR}} \\ \mathbf{T^{MU}} & \mathbf{T^{MM}} & \mathbf{T^{ML}} & \mathbf{T^{MR}} \\ \mathbf{T^{LU}} & \mathbf{T^{LM}} & \mathbf{T^{LL}} & \mathbf{T^{LR}} \\ \mathbf{T^{RU}} & \mathbf{T^{RM}} & \mathbf{T^{RL}} & \mathbf{T^{RR}} \end{bmatrix}$, $\mathbf{x}^* = \begin{bmatrix} \mathbf{x^U} \\ \mathbf{x^M} \\ \mathbf{x^L} \\ \mathbf{x^R} \end{bmatrix}$,

and $\mathbf{y}^* = \begin{bmatrix} \mathbf{y^U} \\ \mathbf{y^M} \\ \mathbf{y^L} \\ \mathbf{y^R} \end{bmatrix}$

where $\mathbf{A}^*$, $\mathbf{x}^*$ and $\mathbf{y}^*$ denote compound regional technical coefficients matrices, total output and domestic final demand for upper reach (U), middle reach (M), lower reach (L) and Rest of China (R), respectively. Then, the compound statement of the basic accounting relations in a four region MRIO model is seen to be:

$$\mathbf{x}^* = \mathbf{T}\mathbf{A}^*\mathbf{x}^* + \mathbf{T}\mathbf{y}^* \qquad \text{Eq. 4-3}$$

so that Eq. 4-3 can be re-arranged as:

$$(\mathbf{I}-\mathbf{TA}^{*})\mathbf{x}^{*}=\mathbf{Ty} \qquad \text{Eq. 4-4}$$

and the solution will be given by

$$\mathbf{x}^{*}=(\mathbf{I}-\mathbf{TA}^{*})^{-1}\mathbf{Ty}^{*} \qquad \text{Eq. 4-5}$$

4.3.2 Virtual water flows and water footprints

I extend the MRIO model by adding a row vector of direct water consumption coefficients in physical unit for the four regions. The direct water consumption coefficient e_j^U is calculated by dividing the total amount of water directly consumed in the *j*th sector by total sector input in the upper reach, which represents the share of water consumption per unit of output in sector *j*. Thus, a row vector of compound water consumption coefficient is shown by:

$$\mathbf{f}^{*}=[\mathbf{f}^{\mathbf{U}} \quad \mathbf{f}^{\mathbf{M}} \quad \mathbf{f}^{\mathrm{L}} \quad \mathbf{f}^{\mathrm{R}}]$$

where $\mathbf{f}^{\mathbf{U}}$, $\mathbf{f}^{\mathbf{M}}$, $\mathbf{f}^{\mathrm{L}}$ and $\mathbf{f}^{\mathrm{R}}$ denote the direct water consumption coefficients of each region.

4.3.2.1 Calculating virtual water flows

In this section, I quantify the virtual water flows among the four study regions. Here, I use upper reach as an example to illustrate how to calculate the regional virtual water flows based on water extended MRIO model. For convenience, the term of $(\mathbf{I}-\mathbf{TA}^{*})^{-1}$ is written as $\mathbf{L}^{*}$ and $\mathbf{Ty}^{*}$ is written as $\mathbf{y}^{\mathbf{U}*}$. The elements of $\mathbf{L}^{*}$ and $\mathbf{y}^{\mathbf{U}*}$ are shown by:

$$\mathbf{L}^{*}=\begin{bmatrix}\mathbf{L}^{\mathrm{UU}} & \mathbf{L}^{\mathrm{UM}} & \mathbf{L}^{\mathrm{UL}} & \mathbf{L}^{\mathrm{UR}}\\ \mathbf{L}^{\mathrm{MU}} & \mathbf{L}^{\mathrm{MM}} & \mathbf{L}^{\mathrm{ML}} & \mathbf{L}^{\mathrm{MR}}\\ \mathbf{L}^{\mathrm{LU}} & \mathbf{L}^{\mathrm{LM}} & \mathbf{L}^{\mathrm{LL}} & \mathbf{L}^{\mathrm{LR}}\\ \mathbf{L}^{\mathrm{RU}} & \mathbf{L}^{\mathrm{RM}} & \mathbf{L}^{\mathrm{RL}} & \mathbf{L}^{\mathrm{RR}}\end{bmatrix} \text{ and } \mathbf{y}^{\mathbf{U}*}=\begin{bmatrix}\mathbf{y}^{\mathrm{UU}}\\ \mathbf{y}^{\mathrm{MU}}\\ \mathbf{y}^{\mathrm{LU}}\\ \mathbf{y}^{\mathrm{RU}}\end{bmatrix}$$

Each element in $\mathbf{L}^{*}$ means that the total inputs are required from shipping region to delivery one unit of final demand for upper reach. Each element in $\mathbf{y}^{\mathbf{U}*}$ indicates that the goods produced in the shipping regions directly consumed by the upper reach's domestic final consumers.

The virtual water imported from the shipping region are consume directly and indirectly in order to satisfy the final demand in the receiving region. As I want to capture the virtual water imported from a specific shipping region to upper reach, $\mathbf{f}^{\mathbf{U}*}$, $\mathbf{f}^{\mathbf{M}*}$, $\mathbf{f}^{\mathbf{L}*}$ and $\mathbf{f}^{\mathbf{R}*}$ only contain the water consumption coefficients for a target region with zeros for the rest of regions.

$\mathbf{f}^{\mathbf{U}*} = [\mathbf{f}^{\mathbf{U}} \quad 0 \quad 0 \quad 0]$, $\mathbf{f}^{\mathbf{M}*} = [0 \quad \mathbf{f}^{\mathbf{M}} \quad 0 \quad 0]$, $\mathbf{f}^{\mathbf{L}*} = [0 \quad 0 \quad \mathbf{f}^{\mathbf{L}} \quad 0]$,

and $\mathbf{f}^{\mathbf{R}*} = [0 \quad 0 \quad 0 \quad \mathbf{f}^{\mathbf{R}}]$

For the upper reach, the total virtual water inflow from middle reach, lower reach and Rest of China can be calculated by:

$$\begin{aligned}
\mathbf{VF}^{\mathbf{MU}} &= \mathbf{f}^{\mathbf{M}*}\mathbf{L}^{*}\mathbf{y}^{\mathbf{U}*} = \mathbf{f}^{\mathbf{M}}\mathbf{L}^{\mathbf{MU}}\mathbf{y}^{\mathbf{UU}} + \mathbf{f}^{\mathbf{M}}\mathbf{L}^{\mathbf{MM}}\mathbf{y}^{\mathbf{MU}} + \mathbf{f}^{\mathbf{M}}\mathbf{L}^{\mathbf{ML}}\mathbf{y}^{\mathbf{LU}} + \mathbf{f}^{\mathbf{M}}\mathbf{L}^{\mathbf{MR}}\mathbf{y}^{\mathbf{RU}} \\
\mathbf{VF}^{\mathbf{LU}} &= \mathbf{f}^{\mathbf{L}*}\mathbf{L}^{*}\mathbf{y}^{\mathbf{U}*} = \mathbf{f}^{\mathbf{L}}\mathbf{L}^{\mathbf{LU}}\mathbf{y}^{\mathbf{UU}} + \mathbf{f}^{\mathbf{L}}\mathbf{L}^{\mathbf{LL}}\mathbf{y}^{\mathbf{LU}} + \mathbf{f}^{\mathbf{L}}\mathbf{L}^{\mathbf{LM}}\mathbf{y}^{\mathbf{MU}} + \mathbf{f}^{\mathbf{L}}\mathbf{L}^{\mathbf{LR}}\mathbf{y}^{\mathbf{RU}} \qquad \text{Eq. 4-6} \\
\mathbf{VF}^{\mathbf{RU}} &= \mathbf{f}^{\mathbf{R}*}\mathbf{L}^{*}\mathbf{y}^{\mathbf{U}*} = \mathbf{f}^{\mathbf{R}}\mathbf{L}^{\mathbf{RU}}\mathbf{y}^{\mathbf{UU}} + \mathbf{f}^{\mathbf{R}}\mathbf{L}^{\mathbf{RR}}\mathbf{y}^{\mathbf{RU}} + \mathbf{f}^{\mathbf{R}}\mathbf{L}^{\mathbf{RM}}\mathbf{y}^{\mathbf{MU}} + \mathbf{f}^{\mathbf{R}}\mathbf{L}^{\mathbf{RL}}\mathbf{y}^{\mathbf{LU}}
\end{aligned}$$

In Eq. 4-6, $\mathrm{f^M L^{MU} y^{UU}}$ is to calculate the imported virtual water from middle reach is required by the upper reach's intermediate demand, in order to satisfy the upper reach's final demand, $\mathrm{y^{UU}}$; $\mathrm{f^M L^{MM} y^{MU}}$ captures the imported virtual water from middle reach is directly consumed by the final consumer, $\mathrm{y^{MU}}$, in the upper reach; $\mathrm{f^M L^{ML} y^{LU}}$ is the imported virtual water from middle reach to lower reach in order to stratify the upper reach's final consumer purchase the goods from lower reach, $\mathrm{y^{LU}}$. $\mathrm{f^M L^{MR} y^{RU}}$ is used for calculating the imported virtual water from middle reach to Rest of China is consumed by the upper reach's final consumer by purchasing goods produced in the Rest of China. The similar explanation of each element above can be also applied to $\mathbf{VF}^{\mathbf{LU}}$ and $\mathbf{VF}^{\mathbf{RU}}$.

Therefore, the total virtual water flows to the upper reach from all other regions can be calculated by:

$$\mathbf{VF}^{\mathbf{U}} = \mathbf{VF}^{\mathbf{MU}} + \mathbf{VF}^{\mathbf{LU}} + \mathbf{VF}^{\mathbf{RU}} \qquad \text{Eq. 4-7}$$

The same approach is also used for calculating virtual water flows for other three regions.

4.3.2.2 Calculating water footprints

This section illustrates how to calculate regional domestic and total water footprints, where total water footprints include rural and urban household water footprints, based on the MRIO framework. To calculate regional domestic and total water footprint, it is important to identify the domestic and total water multiplier which are used to assess supply chain effects of the direct and indirect water consumption to satisfy one monetary unit of final demand. Domestic water multiplier can be denoted by:

$$\begin{aligned} \mathbf{M}_{\mathbf{Dom}}^{\mathbf{U}} &= \mathbf{f}^{\mathbf{U}}(\mathbf{I}-\mathbf{A}_{\mathbf{Dom}}^{\mathbf{U}})^{-1} \\ \mathbf{M}_{\mathbf{Dom}}^{\mathbf{M}} &= \mathbf{f}^{\mathbf{M}}(\mathbf{I}-\mathbf{A}_{\mathbf{Dom}}^{\mathbf{M}})^{-1} \\ \mathbf{M}_{\mathbf{Dom}}^{\mathbf{L}} &= \mathbf{f}^{\mathbf{L}}(\mathbf{I}-\mathbf{A}_{\mathbf{Dom}}^{\mathbf{L}})^{-1} \\ \mathbf{M}_{\mathbf{Dom}}^{\mathbf{R}} &= \mathbf{f}^{\mathbf{R}}(\mathbf{I}-\mathbf{A}_{\mathbf{Dom}}^{\mathbf{R}})^{-1} \end{aligned} \qquad \text{Eq. 4-8}$$

where $\mathbf{M}_{\mathbf{Dom}}^{\mathbf{U}}$, $\mathbf{M}_{\mathbf{Dom}}^{\mathbf{M}}$, $\mathbf{M}_{\mathbf{Dom}}^{\mathbf{L}}$ and $\mathbf{M}_{\mathbf{Dom}}^{\mathbf{R}}$ are domestic water multiplier for upper reach, middle reach, lower reach and Rest of China; $\mathbf{A}_{\mathbf{Dom}}^{\mathbf{U}}$ $\mathbf{A}_{\mathbf{Dom}}^{\mathbf{M}}$ $\mathbf{A}_{\mathbf{Dom}}^{\mathbf{L}}$ and $\mathbf{A}_{\mathbf{Dom}}^{\mathbf{R}}$ denote domestic technical coefficients for the four studying regions. And total water multiplier can be calculated by:

$$\mathbf{M}_{\mathbf{tot}} = \mathbf{f}^{*}\mathbf{L}^{*} \qquad \text{Eq. 4-9}$$

where $M_{tot}$is a row vector of containing sectoral level total water multiplier for the four study regions.

Domestic water footprints are the total water consumed from regional domestic water resource for the total final demand (both domestic final demand and export) in a region. Regional domestic water footprints are calculated by:

$$\begin{aligned} \mathbf{w}_{\mathbf{Dom}}^{\mathbf{U}} &= \mathbf{M}_{\mathbf{Dom}}^{\mathbf{U}}(\mathbf{y}^{\mathbf{U}}+\mathbf{e}^{\mathbf{U}})+\mathbf{w}_{\mathbf{hh}}^{\mathbf{U}} \\ \mathbf{w}_{\mathbf{Dom}}^{\mathbf{M}} &= \mathbf{M}_{\mathbf{Dom}}^{\mathbf{M}}(\mathbf{y}^{\mathbf{M}}+\mathbf{e}^{\mathbf{M}})+\mathbf{w}_{\mathbf{hh}}^{\mathbf{M}} \\ \mathbf{w}_{\mathbf{Dom}}^{\mathbf{L}} &= \mathbf{M}_{\mathbf{Dom}}^{\mathbf{L}}(\mathbf{y}^{\mathbf{L}}+\mathbf{e}^{\mathbf{L}})+\mathbf{w}_{\mathbf{hh}}^{\mathbf{L}} \\ \mathbf{w}_{\mathbf{Dom}}^{\mathbf{R}} &= \mathbf{M}_{\mathbf{Dom}}^{\mathbf{R}}(\mathbf{y}^{\mathbf{R}}+\mathbf{e}^{\mathbf{R}})+\mathbf{w}_{\mathbf{hh}}^{\mathbf{R}} \end{aligned} \qquad \text{Eq. 4-10}$$

Where $\mathbf{w}_{\mathbf{Dom}}^{\mathbf{U}}$, $\mathbf{w}_{\mathbf{Dom}}^{\mathbf{M}}$, $\mathbf{w}_{\mathbf{Dom}}^{\mathbf{L}}$ and $\mathbf{w}_{\mathbf{Dom}}^{\mathbf{R}}$ denotes domestic water footprints for upper reach (upper case **U**), middle reach (upper case **M**), lower reach (upper case **L**) and Rest of China (upper case **R**); $\mathbf{y}^{\mathbf{U}}$, $\mathbf{y}^{\mathbf{M}}$, $\mathbf{y}^{\mathbf{L}}$ and $\mathbf{y}^{\mathbf{R}}$ are regional domestic final demand of the four regions; $\mathbf{e}^{\mathbf{U}}$, $\mathbf{e}^{\mathbf{M}}$, $\mathbf{e}^{\mathbf{L}}$ and $\mathbf{e}^{\mathbf{R}}$ are exports of the four regions; $\mathbf{w}_{\mathbf{hh}}^{\mathbf{U}}$, $\mathbf{w}_{\mathbf{hh}}^{\mathbf{M}}$, $\mathbf{w}_{\mathbf{hh}}^{\mathbf{L}}$ and $\mathbf{w}_{\mathbf{hh}}^{\mathbf{R}}$ denote the direct household water consumption.

Total water footprints are the total water consumption from all water resources to satisfy the regional domestic final demand. Therefore, people living in the region are not only responsible for the water consumed from their domestic water resource, but also the water from other regions' water resources required by their final consumption. The total water footprints for the upper reach can be captured by:

$$\begin{aligned}\mathbf{w}_{\mathbf{Tot}}^{\mathbf{U}} &= \mathrm{M}_{\mathrm{tot}}\mathbf{y}^{\mathbf{U}*} + \mathbf{w}_{\mathbf{hh}}^{\mathbf{U}} \\ &= \mathbf{f}^{\mathbf{U}}\mathbf{L}^{\mathbf{UU}}\mathbf{y}^{\mathbf{UU}} + \mathbf{f}^{\mathbf{U}}\mathbf{L}^{\mathbf{UM}}\mathbf{y}^{\mathbf{MU}} + \mathbf{f}^{\mathbf{U}}\mathbf{L}^{\mathbf{UL}}\mathbf{y}^{\mathbf{LU}} + \mathbf{f}^{\mathbf{U}}\mathbf{L}^{\mathbf{UR}}\mathbf{y}^{\mathbf{RU}} + \mathbf{VF}^{\mathbf{LU}} + \mathbf{VF}^{\mathbf{LU}} + \\ &\quad \mathbf{VF}^{\mathbf{RU}} + \mathbf{w}_{\mathbf{hh}}^{\mathbf{U}}\end{aligned} \qquad \text{Eq. 4-11}$$

where $\mathbf{w}_{\mathbf{Tot}}^{\mathbf{U}}$ is the row vector of total water footprint for the upper reach; $\mathbf{f}^{\mathbf{U}}\mathbf{L}^{\mathbf{UU}}\mathbf{y}^{\mathbf{UU}}$ is used for capturing the upper reach's virtual water flows within the region, $\mathbf{f}^{\mathbf{U}}\mathbf{L}^{\mathbf{UM}}\mathbf{y}^{\mathbf{MU}}$, $\mathbf{f}^{\mathbf{U}}\mathbf{L}^{\mathbf{UM}}\mathbf{y}^{\mathbf{MU}}$ and $\mathbf{f}^{\mathbf{U}}\mathbf{L}^{\mathbf{UR}}\mathbf{y}^{\mathbf{RU}}$ are that the virtual water from upper reach exported to middle, lower reach and Rest of China consumed by upper reach's domestic final consumers by interregional trade; $\mathrm{VF}^{\mathrm{LU}}$, $\mathrm{VF}^{\mathrm{LU}}$and $\mathrm{VF}^{\mathrm{RU}}$ are upper reach's imported virtual water from other three region's domestic water resources. Total water footprints for middle reach, lower reach and Rest of China can be calculated by Eq. 4-12.

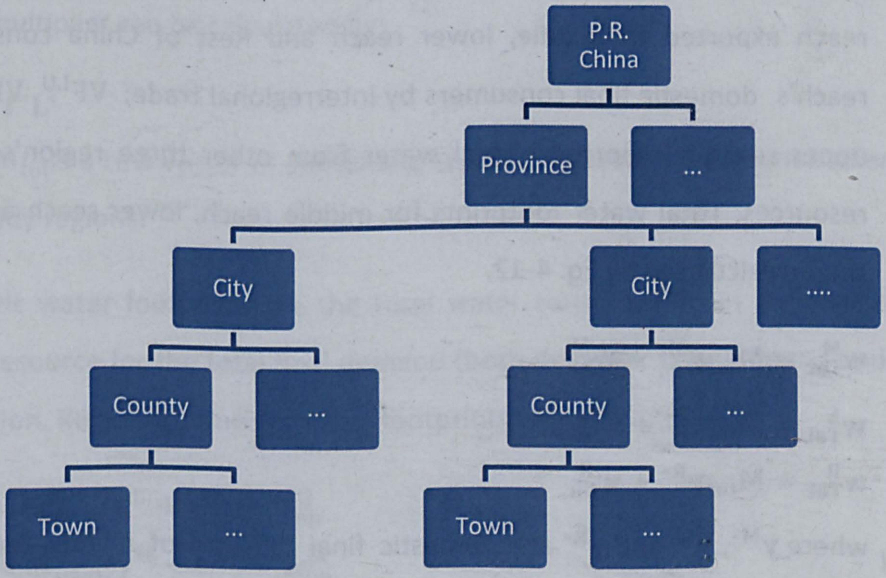
$$\begin{aligned}\mathbf{w}_{\mathbf{Tot}}^{\mathbf{M}} &= \mathbf{M}_{\mathbf{tot}}\mathbf{y}^{\mathbf{M}*} + \mathbf{w}_{\mathbf{hh}}^{\mathbf{M}} \\ \mathbf{w}_{\mathbf{Tot}}^{\mathbf{L}} &= \mathbf{M}_{\mathbf{tot}}\mathbf{y}^{\mathbf{L}*} + \mathbf{w}_{\mathbf{hh}}^{\mathbf{L}} \\ \mathbf{w}_{\mathbf{Tot}}^{\mathbf{R}} &= \mathbf{M}_{\mathbf{tot}}\mathbf{y}^{\mathbf{R}*} + \mathbf{w}_{\mathbf{hh}}^{\mathbf{R}}\end{aligned} \qquad \text{Eq. 4-12}$$

where $\mathbf{y}^{\mathbf{M}*}$, $\mathbf{y}^{\mathbf{L}*}$ and $\mathbf{y}^{\mathbf{R}*}$ are domestic final demand of middle reach, lower reach and Rest of China similar as $\mathbf{y}^{\mathbf{U}*}$ in Eq.4-11.

4.3.3 Data

As the Yellow River passes through nine provinces, the watershed of Yellow River does not align with the administrative boundaries of China. However, any data in China's official statistical database, which are collected from the local governments, are generally defined in terms of administrative boundaries. In order to analyse the water consumption and socio-economic activities within the YRB, administrative boundaries need to be aligned with the watershed. In this study, two types of GIS databases are used; namely, the county level of administrative boundaries GIS database and the Yellow River watershed GIS dataset which contains the Yellow River main stream and its tributaries. Figure 4-3 shows the hierarchical system of China's administrative boundaries. In this study, I match the watershed with the administrative boundaries at the county level which is the most detailed GIS database I have. The counties that fall into the watershed of the YRB are identified. Figure 1 depicts the administrative boundaries in the watershed of the YRB and the main stream and tributaries of the Yellow River. The GIS database for administrative boundaries and the watershed of the YRB are collected from the National Fundamental Geographic Information System of China (NFGIS, 2003).

Figure 4-3: The hierarchy of China's administrative boundaries



This chapter constructs four regional input-output tables which are used for the MRIO model. Three methods to construct IO table are frequently used in the literature: survey based, semi-survey and non-survey techniques (Miller and Blair, 2009). The survey based and semi-survey approaches have high accuracy but at high cost and are time consuming (Miller and Blair, 2009). The non-survey approach commonly applied the Location Quotient technique using detailed sectoral economic data such as labour data or value added to adjust the technical coefficients to reflect the actual size of the respective section within the study region. However, these data are not available at county level in the YRB. A scaling method which is based on proportional spatial distribution is applied to the 2002 provincial IO table by using the total economic output of aggregated agriculture, industry and service sector in the identified counties. Then, I merge the adjusted provincial IO tables in each reach to create three regional IO tables for the YRB. The Rest of China IO table are obtained from China's national table by removing the three region's intermediate and final demands in the YRB.

The 2002 IO tables (76 by 76 sectors) for the nine provinces are collected from the National Statistical Bureau of China. The input-output tables include 6 agriculture sectors, 44 industry sectors and 26 service sectors, where the detailed agricultural sectors are including Crops, Livestock, Forestry, Logging and transport of timber and bamboo, Fishery, Agricultural services. The regional trade data are estimated from regional transportation flow data which are collected from China Transport Statistical Yearbook (State Statistical Bureau of China, 2003). Finally, the blue water consumption data by sectors (agriculture, industry, service sectors) are collected from Yellow River Water Resources Bulletins published by Yellow River Conservancy Commission (YRCC) (YRCC, 2002b). The industry and service sectors' water consumption is further disaggregated into 70 sectors according to the sectoral waste water discharge which are collected from the provincial statistical yearbooks (State Statistical Bureau of China, 2004). The water consumption of each non-agricultural sector is the sectoral direct water withdrawal subtracted by the water returned back to the watershed (blue water). In this chapter, I consider only Crops sector consumes green water. Green water is calculated by multiplying the sown areas of different crops by their water requirements per hectare and then subtracting their blue water consumption. the water requirements per hectare of different crops are collected from Zhu *et al.* (2003a)

4.4 Results

4.4.1 Supply chain effects

Direct water coefficient and water multiplier are useful indicators to assess the efficiency of each sector in terms of water consumption per unit of output. In this study the input-output tables include 76 sectors. However, regional water consumption is only substantially affected by a small number of major water consuming sectors. The direct water coefficients and domestic and total water multipliers of a number of key economic sectors are presented in Tables 4-3 and 4-5. These economic sectors are selected either because of their large water intensity, or because of their importance for final demand in monetary terms.

Direct water coefficient is the direct water consumption to produce one unit of sectoral output in monetary value, and it indicates the direct effects of production activities on its domestic water resources. From Table 4-3 I can see that Crops requires the largest direct water input per unit sectoral output in all four regions followed by Livestock, Electricity and steam production, Paper, printing and publishing and Processed food products. Table 4-3 also shows a huge regional difference of sectoral direct water coefficient among the four study regions. Apparently, most of the key sectors in the upper reach have larger direct water coefficient than the same sectors in the other three regions. This indicates that the water consumption of the key economic sectors in the upper reach are generally higher than in the other three regions. Particularly, the water consumption in the upper reach to produce 10,000 Yuan of crops is more than double of the water consumption in the other regions.

Table 4-3: Direct water coefficients for 16 key economic sectors (m^3/10,000 Yuan)

Sector	Upper	Middle	Lower	RoC
Crops	6022.1	5464.9	3291.5	5006.6

Livestock	659.3	235.6	55.2	170.6
Grain mill products	60.6	21.4	16.9	14.7
Meat products	60.6	21.4	16.9	14.7
Other processed food	60.6	21.4	16.9	14.7
Alcoholic beverages	56.7	17.6	14.0	14.7
Textile and fibres	8.8	9.2	12.1	14.9
Leather and fur	9.3	5.8	7.0	5.1
Wearing apparel and footwear	18.8	38.5	6.0	5.1
Paper, printing and publishing	112.6	46.6	60.2	21.6
Chemicals	57.1	33.6	18.1	26.2
Transport equipment	1.0	4.4	1.5	3.9
Electricity and steam production	139.9	77.4	91.3	56.5
Construction	19.0	8.5	11.2	6.9
Hotel and catering services	7.0	5.8	5.7	4.0
Health services	7.3	6.1	6.0	4.2

Note: RoC denotes Rest of China.

The production of crops accounted for more than 85 percent of the total direct water consumption in the YRB; thus it is very important to investigate why the direct water intensity of crops in the lower reach is much lower than the intensities in the two other reaches and the Rest of China as bench mark. In the three reaches of YRB, most of the agriculture areas are used for the production of wheat, maize, soybean, oil crops and cotton. From regional statistical database and the irrigation water use data presented by YRCC, I found that two main factors cause the regional difference of direct water coefficients for cropping. One is because of the differences of land productivity for crops in the studying regions. Table 4-4 shows that land productivities for most crops in the lower reach are higher than the other region's productivities, and in particular, the productivity of wheat in the lower reach is about 45 percent higher than the productivity in the middle reach and 76 percent higher than the one in the upper reach. The huge difference, in terms of land productivities, can be also observed from soybean, tubers and oil crops.

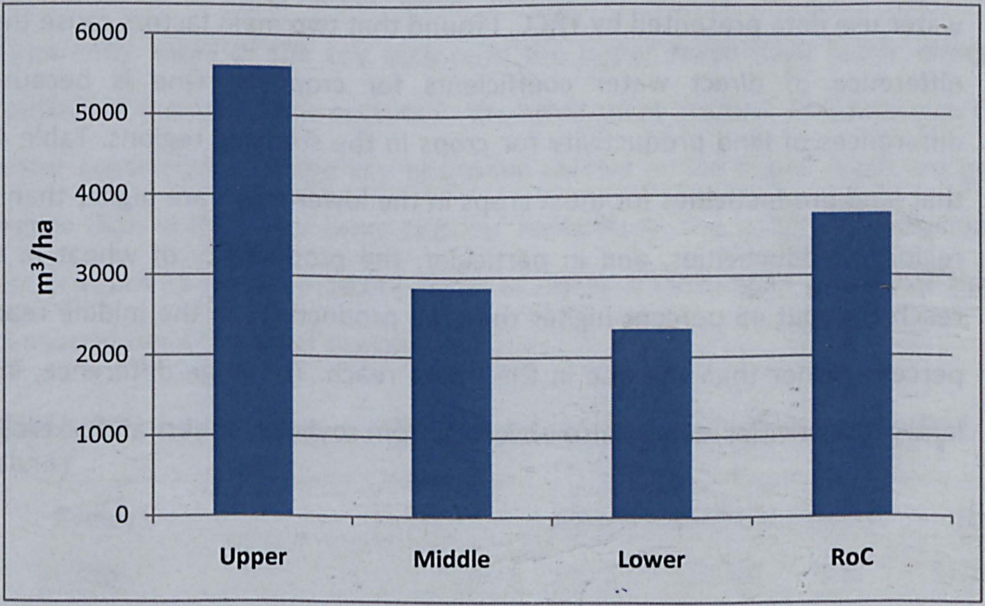
Table 4-4: Land productivities of the three reaches in the YRB (ton/ha)

	Upper	Middle	Lower	RoC
Wheat	2.78	3.38	4.91	3.93
Maize	4.34	4.57	4.54	4.81
Soybean	1.39	1.01	1.86	1.65
Tubers	3.29	2.73	4.98	3.62
Oil crops	1.38	1.29	2.77	1.88
Cotton	0.68	0.91	0.70	0.95

Source: Provincial Statistical Yearbooks (2004)

The other factor is irrigation water use per hectare of irrigation land, which is an important indicator for the water efficiency of irrigation systems. From Figure 4-4 I can observe that the lower reach has the smallest irrigation water use per irrigation land, which is less than half of the irrigation water use per irrigation land in the upper reach. This also can partly explain why the larger water coefficient in the upper reach compared to the middle reach and Rest of China. However, the water coefficient in the middle reach is larger than the coefficient for Rest of China, while the irrigation water use per irrigation land is smaller in the middle reach. This might be due to the better land productivities in other parts of China which overwhelmed the effects from the larger irrigation water use per irrigation land on the direct water coefficient.

Figure 4-4: Average irrigation water use per unit of irrigation land (m^3/ha)



Note: Irrigation water use is the irrigation water withdrawal minus the water flow back to the basin, which is defined as blue water in this study.

Domestic water multiplier is the water intensity of economic sectors from the domestic water resources after tracing the regional domestic supply chain, thus it is a useful indicator to assess the supply chain efficiency of utilising the domestic water resources for regional production activities. From Table 4-5 I can observe that the domestic water multipliers for all economic sectors are larger than their direct water coefficients after tracing the supply chain effect within the region. Particularly, water requirements of many secondary and tertiary sectors from domestic water resource are increased dramatically, as these sectors need a huge amount of inputs from primary sectors, such as Crops and Livestock, to produce their own products for the final consumers, whereas there is no big difference between direct water coefficient and domestic water multiplier for crops and Electricity and steam production because of their low water input from other economic sectors. After tracing the domestic supply chains effects, the Livestock and most of processed food products, such as Grain mill products, have very large water coefficients as well as Textile and fibres and Leather and fur.

Table 4-5: Domestic and total water multiplier for 16 key economic sectors (m^3/10,000 Yuan)

Sector	Upper		Middle		Lower		Rest of China	
	Domestic	Total	Domestic	Total	Domestic	Total	Domestic	Total
Crops	6,636	6,727	6,305	6,351	3,863	3,865	5,417	5,421
Livestock	1,904	2,213	1,976	2,069	1,389	1,534	1,766	1,762
Grain mill products	2,063	2,697	2,617	2,866	1,271	1,838	3,669	3,693
Meat products	662	1,104	787	884	744	1,119	1,300	1,299
Other processed food	1,269	1,415	1,643	1,782	1,365	1,999	1,164	1,165
Alcoholic beverages	868	954	1,305	1,401	1,697	2,431	1,377	1,379
Textile and fibres	273	370	1,542	1,632	2,088	2,907	942	949
Leather and fur	819	974	511	570	915	1,298	429	436
Wearing apparel and footwear	248	340	449	529	557	929	418	429
Paper, printing and publishing	537	580	790	875	702	1,117	160	164
Chemicals	183	228	674	755	387	660	144	148

Transport equipment	80	95	78	114	226	382	47	5
Electricity and steam production	201	215	137	158	208	262	82	8
Construction	68	97	86	127	175	267	385	39
Hotel and catering services	494	728	479	606	302	385	514	52
Health services	55	90	107	143	137	169	87	9

Direct water coefficient and domestic water multipliers exclusively concentrate on the water intensity of local production activities from domestic water resource, which ignore the supply chain effects on water resources in other regions. Nevertheless, it is important to assess the water efficiency taking the whole intra-regional and inter-regional supply chain effects into account. Table 4-5 shows that compared to the domestic supply chain effect some key sectors have large increase of water consumption per monetary unit of final delivery in each region after tracing the whole supply chain effect. In the upper reach Meat products, Grain mill products, Textile and fibres and Hotel and catering services have much larger total water multipliers than their domestic water multipliers, while only three sectors are in middle reach: Transport equipment, Construction and Health services. In the lower reach, total water multipliers are much larger than domestic multipliers for most sectors due to a large amount of water-intensive goods required from outside of the region, except for Crops.

4.4.2 Regional virtual water flows

Virtual water flows are measured by the embedded water in trade among different regions. Virtual water in trade can significantly influence the region's "water consumption responsibility". In this section, I use virtual water flows to assess how the water as an input for economic activities has been imported or exported virtually among four study regions and how the results can help solve regional water scarcity by redistribution of water resources from water-rich to water-poor regions. Table 4-6 shows the regional virtual water balance in the upper, middle and lower reaches and the Rest of China. This chapter is based on the four region MRIO framework without taking international trade into account. From Table 4-6, I can observe that the whole YRB is net virtual water exporter when I take both green and blue water into account. It means that the total virtual water exported from each region in the YRB is larger than the total virtual water imported to each region. By distinguishing blue and green water, I found that the upper reach is net green water importer and net blue water exporter, whereas the middle reach is a net green water exporter and net blue water importer. The lower reach is the net exporter for both green and blue water. In total, the whole YRB has a net export of 6,920 million m^3 (approximate 10 percent of total water consumption in the YRB) virtual water to the Rest of China.

From Table 4-6 I also can observe that the trade flows between the three reaches in the YRB are much smaller than their trade flows with the Rest of China. In particular, the middle reach exports 30 percent of green water and 32 percent of blue water to the Rest of China, while lower reach exports 15 percent of both green and blue water to the Rest of China. However, the virtual water flows between the three reaches are around 1 - 3 percent of their domestic water in each region.

Table 4-6: Virtual water flows between the four studying regions (in million m^3)

			Receiving region					
			Upper	Middle	Lower	Rest	Total outflow	Net outflow
Shipping region	Upper	Green	4,978	166	39	2,047	**7,230**	**-1,675**
		Blue	9,312	389	92	4,596	**14,389**	**2,687**
	Middle	Green	257	20,436	422	9,035	**30,150**	**5,441**
		Blue	83	5,876	150	2,911	**9,020**	**-46**
	Lower	Green	45	198	9,673	1,792	**11,708**	**292**
		Blue	32	145	6,383	1,134	**7,694**	**221**
	Rest	Green	3,625	3,909	1,282	415,545	**424,362**	**-4,057**
		Blue	2,275	2,656	849	250,597	**256,377**	**-2,862**
		Total inflow	**20,606**	**33,775**	**18,889**	**687,658**	**760,928**	

Note: RoC denotes Rest of China; Net outflow is total regional outflow minus total regional inflow.

4.4.3 Regional domestic and total water footprints

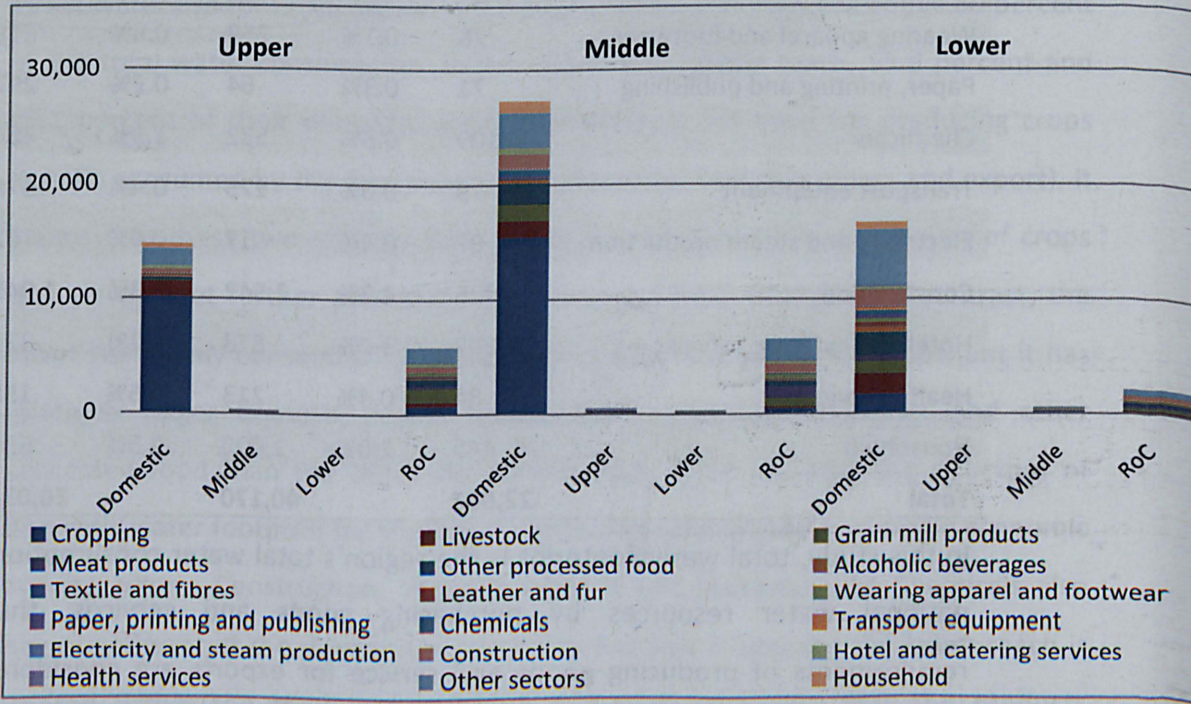
In this section, I assess domestic and total water footprints for the three reaches in the YRB and the Rest of China. Domestic water footprint is equal to the total of virtual water flows from shipping region to receiving region which is shown in Table 4-6, plus the regional household direct water consumption. Domestic water footprint is the total water consumption from regional domestic water sources; this includes domestic water consumption for regional production activities and household water use. Therefore, it is a useful tool to assess the effects of regional production and consumption activities on local water sources. From Table 4-7 I can observe that after tracing the supply chain effects, the share of water consumption for Crops sector is much smaller than usually claimed in the literature (e.g. Chapagain and Orr, 2008; Hoekstra and Chapagain, 2007, 2008) and the share of direct water use for Crops sector in the study, which generally are above 80 percent of the total water consumption. In the upper and middle reach, 55.9 percent and 47.1 percent of their domestic water consumption are used for producing crops directly consumed by the final consumers (domestic final consumers and export). It means that these two region's final consumers consume a large amount of crops directly without further processing for processed food products. In contrast, the lower reach only consumes 7.2 percent of its domestic water for Crops, but it has relatively larger domestic water footprints for grain mill products and other processed food than the other sub-basins. Also, I can see that the structure of domestic water footprint for the lower reach is less dominated by a single economic activity, where Construction, Wearing apparel and footwear and Chemicals also have significant of the domestic water footprint. This is because the lower reach is located within the more industrialized east-coast of China, thus the products produced from primary sectors are prepared and further processed by industry sectors for regional final use or are further exported to other regions. However, the lower reach has the highest share of direct water consumption for Crops sector (93 percent of total regional direct water consumption) and the lower reach is the most water scarce region in the basin. This clearly reflect water problems in the lower reach where higher value added production and services might be constrained by less water availability that is generously used up for lower value added agricultural products.

Table 4-7: Domestic water footprints of key economic sectors in the YRB (million m^3)

	Upper		Middle		Lower	
Crops	12,339	55.9%	18,911	47.1%	1,581	7.9%
Livestock	2,911	13.2%	2,412	6.0%	1,681	8.4%
Grain mill products	232	1.1%	1,780	4.4%	1,107	5.5%
Meat products	173	0.8%	593	1.5%	906	4.5%
Other processed food	1,253	5.7%	2,480	6.2%	2,248	11.2%
Alcoholic beverages	368	1.7%	640	1.6%	621	3.1%
Textile and fibres	15	0.1%	1,142	2.8%	555	2.8%
Leather and fur	112	0.5%	134	0.3%	357	1.8%
Wearing apparel and footwear	28	0.1%	259	0.6%	618	3.1%
Paper, printing and publishing	71	0.3%	64	0.2%	297	1.5%
Chemicals	109	0.5%	532	1.3%	464	2.3%
Transport equipment	9	0.0%	175	0.4%	378	1.9%
Electricity and steam production	87	0.4%	17	0.0%	61	0.3%
Construction	925	4.2%	2,542	6.3%	1,945	9.7%
Hotel and catering services	697	3.2%	878	2.2%	327	1.6%
Health services	84	0.4%	213	0.5%	158	0.8%
Household	445	2.0%	1,000	2.5%	634	3.2%
Total	**22,063**		**40,170**		**20,036**	

In this study, total water footprint is the region's total water consumption from all national water resources by purchasing goods and services, thus water requirements of producing goods and service for exports are considered as the responsibilities of the final consumers in the importing region. Total water footprint can be used for identifying how much the region consumption rely on its domestic water resources and the water resources in other regions in China. Therefore, I can assess the contributions for reducing the domestic water stresses from other regions. Figure 4-5 provides an explicit illustration of total water footprints for the regions in the YRB, which decomposed the amount of water consumed by local consumption activities from domestic water resources and water source located in other regions. From Figure 4-5, I can see that the middle reach has the largest total water footprint in the YRB followed by middle and lower reaches, where 31 percent, 28 percent and 10 percent of total water footprints for upper, middle and lower reaches are from purchasing goods and services which consuming water from the Rest of China's water resources. From Figure 4-5 I can also see that the total water footprints of three reaches from external water resources are mixed by the import of secondary products produced by industry and services sectors rather than the usually dominated Crops sector. It is also interesting to point out that the lower reach as the most water scarce region in the basin has the lowest share of total water footprint from imports, which is clearly a disadvantage for reducing the water burden in the region.

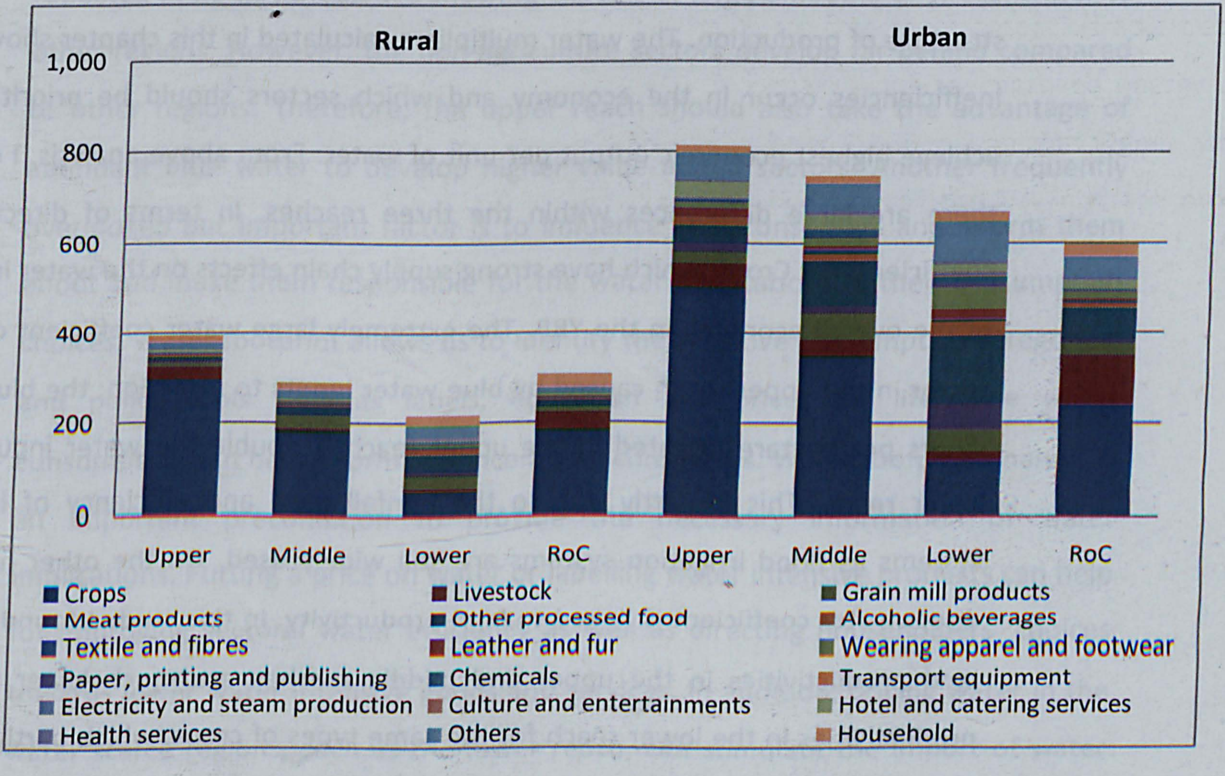
Figure 4-5: Regional total water footprints of the YRB (million m^3)



4.4.4 Water footprints of urban and rural households

This section links water consumption to household consumption patterns distinguished by rural and urban areas in the three reaches of the YRB and the Rest of China as a bench mark. The results in Figure 4-6 shows that the regional household water footprints are significantly driven by the water intensity of crops where the crops produced in upper reach have much higher water intensities than other regions. In particular, crops account for 76 percent and 62 percent of rural household water footprint in the upper and middle reaches. Thus, rural household in upper reach has the highest rural household water footprint per person followed by the rural household in middle reach. Rural household water footprint per person in the upper reach is 33 percent and 82 percent higher than the water footprint in the middle and lower reaches and 25 percent higher than the one in Rest of China. However, the gaps among three reaches become much smaller in terms of urban household water footprints. There are two main factors playing important role for narrowing the gaps. One is the increase of household consumption comparing urban household to rural household. In the lower reach, the consumption of urban household is 3.9 times of the rural household, while the increase rate reduces to 3.7 times for middle reach and 3.4 times for upper reach. The other is the changes of consumption structures. It can be clearly observed that the consumption of non-primary products share 39 percent and 53 percent of urban household water footprint in the upper reach and middle reach compared to 24 percent and 38 percent for the rural area.

Figure 4-6: Household total water footprints per person in the YRB and the Rest of China (m^3/cap/year)



From Figure 4-6 I also notice there are huge differences between the urban household water footprints and rural household water footprints in the basin and Rest of China. The differences are substantially driven by the high consumption of non-primary products, such as Processed food products and Wearing apparel and footwear. This is due to the much higher income levels of urban households, thus consume more on luxury household goods and personal beauty.

4.5 Discussion and conclusions

Based on the four regions MRIO model, this study provides a systematic framework for assessing the regional virtual water flow and water footprints at sector level with limited data sources. Also, this chapter demonstrates the usefulness of a multi-regional accounting framework for assessing the water footprint of production and consumption activities in interdependent economies. In addition, this framework can be used for identifying the key water consumption sectors, in terms of both direct and indirect effects, which can provide useful information for reducing regional water scarcities to the local and regional policy makers.

Given a water constraint economy can either increase supply (e.g. through water transfer), increase water productivity, decrease final demand or change the structure of production. The water multipliers calculated in this chapter show were inefficiencies occur in the economy and which sectors should be prioritized to achieve highest economic output per unit of water. From above analysis, I can see there are large differences within the three reaches, in terms of direct water coefficients for Crops, which have strong supply chain effects on the water intensity of the overall economy in the YRB. The extremely large water coefficient of Crops sector in the upper reach caused by blue water inputs to irrigation; the blue water inputs per hectare irrigated in the upper reach is double the water input in the lower reach. This is partly due to the rainfall level and efficiency of irrigation systems as flood irrigation systems are still widely used. On the other hand, the direct water coefficient is linked to land productivity. In this study I found that the land productivities in the upper and middle reaches are much lower than the productivities in the lower reach for the same types of crops, which partly induced by the low efficient of the irrigation system in those two reaches. Therefore, to improve the water productivities, the upper and middle reach should invest in more modern irrigation techniques, which might substantially improve the efficiency of irrigation systems, at the same time increasing land productivities. .

As most regional government policies on sustainable water management solely focus on local water resources, the virtual water flows can provide an option for solving the regional water scarcity. The results on the regional virtual water flows and regional water footprints indicate that the lower reach is a net virtual water exporter for both blue and green water. As the most water scarce region in the YRB, the lower reach exports about 16 percent of its blue water to other areas through inter-regional trade, in particular crops and processed food products. The lower reach can substantially benefit from reducing the export of water intensive and low value added products and using the blue water for the production of higher value added products, in the meantime, importing these high water intensive and low value added products from water-rich regions, particularly from the water abundant South of China. The upper reach is a comparatively water-rich region which is also reflected in its water balance showing exports of large amounts of virtual water to other regions. However, the non-agriculture sectors develop far behind compared to other regions. Therefore, the upper reach should also take the advantage of abundant blue water to develop higher value added sectors. Another frequently overlooked but important factor is to influence final consumers and inform them about and make them responsible for the water implications of their consumption choices. Water footprint allows us to identify the sensitive consumption categories; and policy tools such as labels, education and prices for life cycle water consumption can help inform and incentivise consumers. Water footprint analysis is an important precondition to provide the necessary information of water implications. Putting a price on water or labelling water intensive products can help for improving sectoral water efficiency as well as directing householders' choices towards lower water intensive goods and services. In addition, pricing water in the water scarce regions, such as the lower reach, can stimulate the import of water intensive goods and reduce the stress on domestic water resources. Water as a significant factor for regional sustainable development should be taken into account along with other environmental factors, such as land accessibility and local infrastructure, for the regional and national policy making.

Chapter 5 : A Regional Comparative Analysis of the Driving Forces of China's CO_2 Emissions 2002-2007

Structural decomposition analysis (SDA) is also a powerful extension of input-output modelling to identify the key socio-economic drivers of environmental issues. However, all the studies in the past were exclusively focused at national level, while the regional disparities were generally ignored. In this chapter, I carry out a SDA study to assess the regional changes in CO_2 emissions triggered by population growth, lifestyle changes, urbanisation, economic structure transitions, technology improvements and export for 28 regions in China.

5.1 Introduction

China's carbon dioxide (CO_2) emissions have almost doubled from 2002 to 2007, and it is recognised that China already surpassed the United States to become the largest CO_2 emitter of the world between 2006 and 2007(Guan et al., 2009; IEA, 2007; MNP, 2007). This causes increasing international pressure on China to curb the fast growth of its emissions. Recently, China has committed to reduce its CO_2 emissions per unit of Gross Domestic Product (GDP) by 40 to 45 percent from 2005 levels and use non-fossil fuels for about 15 percent of its energy generation by 2020 (NRDC, 2009). However, focussing on carbon intensity alone may not be enough as there are also many other driving forces such as urbanisation, consumption pattern, economic structure and population growth. In addition, rather than a homogenous country that can be analysed at the national level, China is a vast country with significant differences with regards to physical geography, local economy, demographics, industry structure and household consumption. In particular, there are pronounced differences between the much-developed Eastern-Coastal zone and the less developed Central and Western zones of China. Such variations lead to large regional discrepancies in terms of CO_2 emissions.

Two decomposition approaches have been frequently used for assessing the key driving forces for energy consumption and CO_2 emissions at the sectoral level: Index Decomposition analysis (IDA) and Structural Decomposition Analysis (SDA). IDA has been developed based on the index theory focusing on the specification of the decomposition (Ang and Liu, 2001; Ang et al., 2004; Ang and Zhang, 2000; Hoekstra and van den Bergh, 2002). Numerous studies have been carried out using IDA to analyse energy consumption and energy related CO_2 emissions in China for different time periods. For example, Ang and Pandiya (1997) presented two methods for decomposing energy-induced CO_2 emissions in the manufacturing sector based on the Divisia index approach and applied the methods to examine the change in emission intensities in China, South Korea and Taiwan. The Authors found that energy intensity has the largest impact on the changes in the aggregate CO2 intensities in China for the time period 1980 – 1991. Wang *et al.* (2005) carried out a study on analysing the change of aggregated CO2 emissions in China from 1957 to 2000 based on the Logarithmic Mean Divisia Index (LMDI) method. The findings indicated that a considerable decrease of CO_2 emissions in the study period was mainly due to improved energy intensity and China's CO_2 emissions would have been 2,466 million tons higher without improvement in energy intensity. Wu *et al.* (2005) used the IDA and the provincial aggregate data to assess the underlying driving forces behind the stagnancy of energy-related CO_2 emissions in China from 1996 to 1999 and the results showed that decrease in energy intensity and a slowdown in the growth of average labour productivity of industry sectors were the main contributors to the "stagnancy" of China's energy-related CO_2 emissions. Liu *et al.* (2007) also applied the LMDI approach to examine the change of China's industrial CO_2 emissions from final fuel use. The authors found that the industry activity and energy intensity were the dominant drivers for the change of industrial sectors' carbon emissions in China between 1998 and 2005. Feng *et al.* (2009) carried out a regional comparative analysis on China's lifestyles, technology and CO_2 emissions from 1952 to 2002 using Impact Population Affluence Technology (IPAT) model and observed that fast growth of the household consumption was the main driver for the CO_2 emissions growth in the five study regions and China as a whole since 1978 although emissions intensity tended to driving the emissions down. Zhang *et al.* (2009) used IDA approach to account for energy-related CO_2 emissions in the time period 1991 – 2006 in China. They also found that energy intensity was the dominant contributor to the decline in CO_2 emissions while economic activity was the key contributor to increase CO_2 emissions. IDA has the advantage of a low data requirement, while this is also a disadvantage as less detailed decomposition of the economic structure (Hoekstra and van den Bergh, 2002). In addition, IDA approach cannot analyse the interdependency of different economic sectors. Through the review of the literature on IDA approach, I found that most of IDA studies focused on energy intensity changes, while other socio-economic factors have been either ignored or only briefly discussed at aggregate level.

SDA generally refers to decomposition analysis based on input-output analysis (IOA) and data (Miller and Blair, 2009). Peters et al. (2007) and Guan *et al.*(2008) amongst others have conducted SDA studies on how changes in technology, economic structure, urbanisation and lifestyles impact on CO_2 emissions in China in the time period 1992 – 2002 and 2002 – 2005, respectively. The key findings of their studies are that the growth of CO_2 emissions significantly caused by infrastructure construction and urban household consumption. Technology and efficiency improvements only partially offset consumption growth. Later on, Guan *et al.*(2009) carried out an IO-IPAT SDA study on analysing the drivers of Chinese CO_2 emissions from 1980 – 2030 and predicted that China's production-related CO_2 emissions would increase threefold by 2030. The study concluded that household consumption, capital investment and growth in export will drive the growth in CO_2 emissions, and efficiency gain would offset the projected increases in consumption, but would not be sufficient if China's household consumption patterns converge to current Levels in the U.S.. Several advantages lead us to use SDA approach for this study. Firstly, SDA overcomes many of the static features of IO models and enables the evaluation of changes over time in technical coefficients and structure mix. Secondly, SDA is capable of distinguishing a range of production effects and final demand effects that is not feasible in IDA approaches. Thirdly, SDA requires only at least two I-O tables, one for the initial year and one for the terminal year of the analysis, whereas econometric estimation requires a long time series of data. Last but not least, the IO SDA is able to capture both direct and indirect effects along the whole supply chain (Miller and Blair, 2009).

In the past, most of IDA and SDA studies on China focused on national CO_2 emissions, while the regional socio-economic differences are ignored. For instance, the economic development, urbanisation, technology improvement and income growth are very different between well-developed Eastern-Coastal regions and under-developed Central and Western regions in China, thus the key driving forces of CO_2 emissions may vary from different regions in China. A study of regional SDA can provide better information for the climate change mitigation policy design and implementation for China where regional disparities which need to be taken into account. Using regional input-output tables in China from 2002 and 2007 (i.e. 28 regions in total) and structural decomposition analysis (SDA), I analyse how the changes in population, technology, economic structure, urbanization, household consumption patterns and export affect regional CO_2 emissions and identify the key economic sectors that drive the emission in each region. This study covers most regions in China except Tibet, Qinghai and Chongqing due to a lack of data.

5.2 Background

Since the national Seventh Five-Year Plan, China set up the “three economic zones” division, comprising the Eastern-Coastal, Central and Western regions (State Council of China, 1986). The Eastern-Coastal economic zone contains eight provinces and three municipalities[3], and it is the most economically developed region in China due to high level of industrialization and fast growth of international trade which play a significant role in linking China’s economy to the world market. However, comparatively speaking, the economic development in Guangxi lags far behind all other provinces in the Eastern-Coastal economic zone and its economic characteristic is very similar to the provinces in western China. Thus, in this study, Guangxi is grouped into the Western economic zone (see Figure 5-1). The Central

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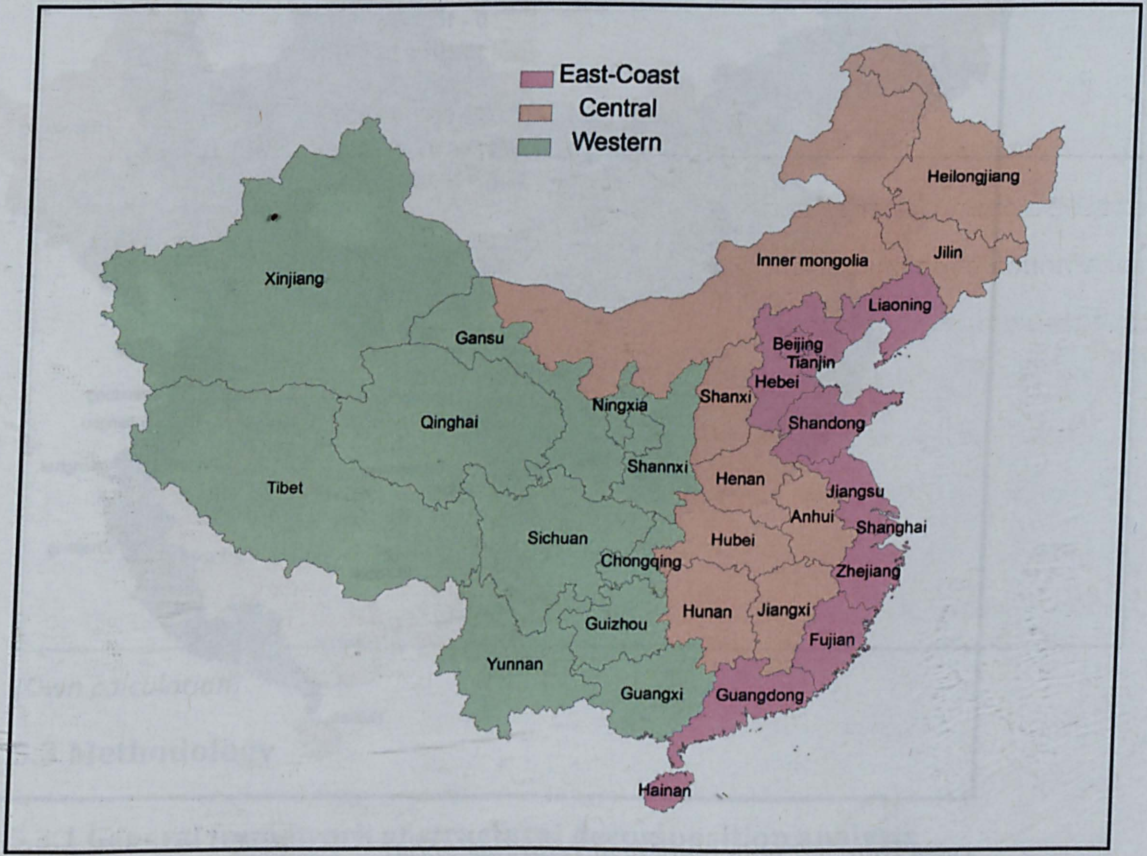
[3] Eight provinces are Fujian, Guangdong, Hainan, Hebei, Jiangsu, Liaoning, Shandong, Zhejiang, and three municipalities are Beijing, Tianjin and Shanghai.

economic zone consists of nine provinces[4] where the economic infrastructure is relatively well-established compared with the Western economic zone but under-developed compared with the Eastern-Coastal economic zone. The Central economic zone has abundant natural resources, such as coal, oil and metals ores, which provide strong basis for its regional economic development. The Western economic zone is the least developed region in China. It consists of ten provinces (including Guangxi) and one municipality[5]. However, since the launch of China's Western Development Programme in 2000, the growth of the economy in the Western economic zone has been steadily on the rise but it still lags far behind when compared to the Eastern-Coastal zone.

Figure 5-1: Three economic zones in China: Eastern-Coastal, Central and Western



Note: The four Municipalities are Beijing, Tianjin, Shanghai and Chongqing. – say why they are listed separately

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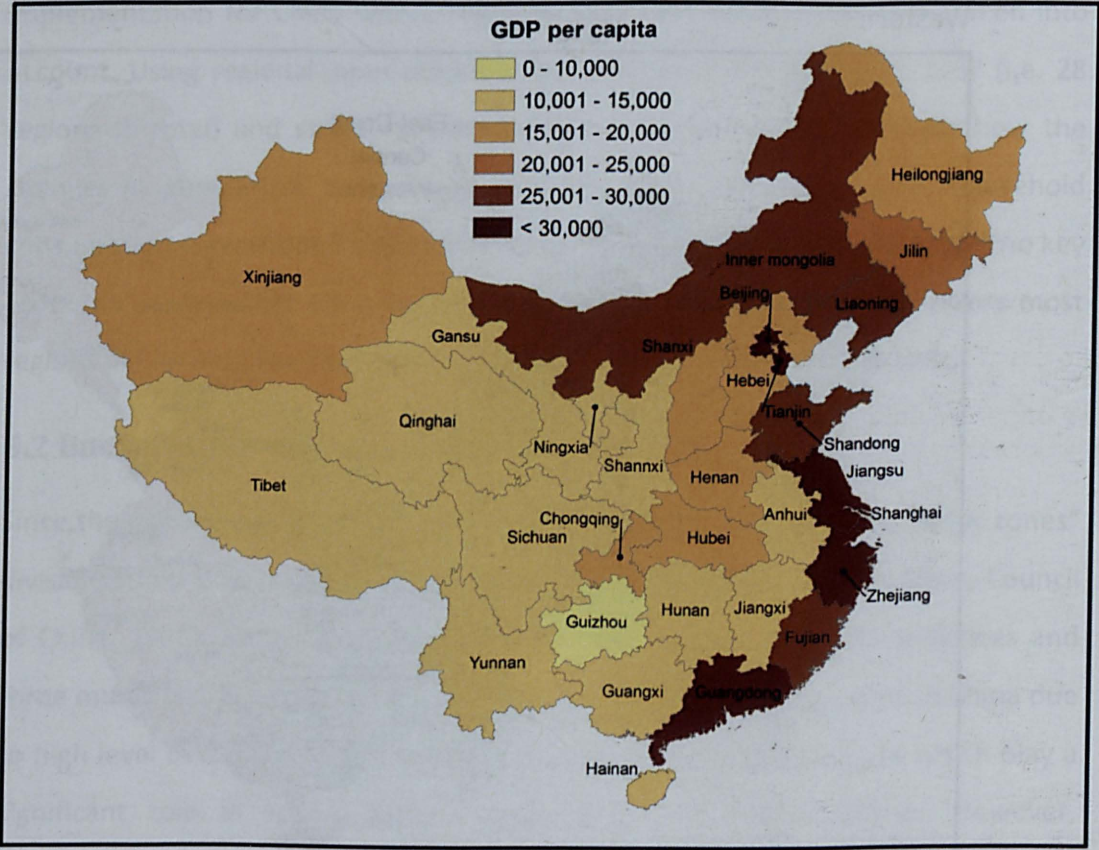
[4] Nine provinces are Anhui, Heilongjiang, Henan, Hubei, Hunan, Inner Mongolia, Jilin, Jiangxi and Shanxi.

[5] Ten provinces are Gansu, Guizhou, Guangxi, Ningxia, Qinghai, Shannxi, Sichuan, Yuannan, Xinjiang and Xizhang, and one municipality is Chongqing which has been separated from Sichuan province since 1997.

Data source (State Council of China, 1986)

Figure 5-2 shows China's regional per capita GDP in 2007. In this figure, the territorial boundary of the three economic zones shows a big gap of regional economic development where the Eastern-Coastal regions are much more developed and higher per capita GDP than the Central and Western regions. It is also worth noting that Inner Mongolia, which is in the Central economic zone, has already caught up with the Eastern-Coastal region in terms of per capita GDP driven by a fast growth of industrialization and domestic exports to other regions in China (National Statistical Bureau of China, 2003-2008).

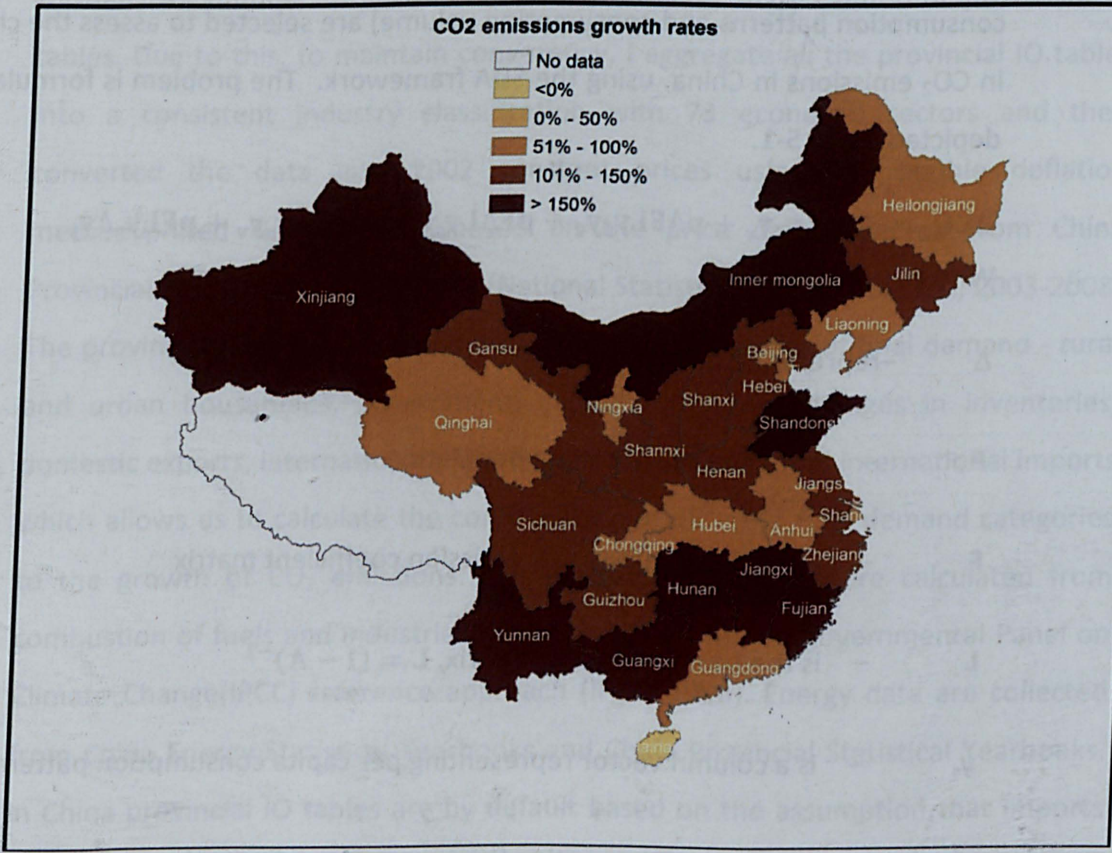
Figure 5-2: China's regional GDP per capita in 2007 (in Yuan)



Data source (China Statistical Yearbook 2008)

Figure 5-3 shows that China's CO2 emissions rapidly increased from 2002 to 2007. In general, CO_2 emissions increased by more than 50% for most regions and more than doubled for approximately two thirds of China's regions during this time period. Also, it can be observed that in Figure 5-3, there are no pronounced differences between the three economic zones in terms of the growth of CO_2 emissions. However, different regions play very different roles in shaping China's economy and may therefore have different factors in influencing CO_2 emissions. Thus, to reduce China's overall CO_2 emissions, it is important to identify the main drivers for the growth of regional CO_2 emissions so that mitigation options can be suggested at the appropriate spatial scale.

Figure 5-3: The growth rates of regional CO_2 emissions from production activities in China, 2002-2007



(Own calculation)

5.3 Methodology

5.3.1 General framework of structural decomposition analysis

Structural Decomposition Analysis (SDA) is a common descriptive tool which has frequently been used by many countries to analyse the key driving forces and industry sectors of changes of energy and CO_2 emissions over time at national level such as Australia (Wood, 2009), Denmark (Rormose and Olsen, 2005; Wier, 1998), India (Mukhopadhyay and Chakraborty, 1999), Korea (Lim et al., 2009), Netherlands

(Wu et al., 2005), the United States (Casler and Rose, 1998) and China (Guan et al., 2008; Guan et al., 2009; Peters et al., 2007). Over a given period of time, any changes in energy demand and associated CO_2 emissions in a country or region may be caused by a variety of factors such as changes in population growth, economic output, infrastructure investment, efficiency improvement, technology, and the production and consumption systems. SDA has become a commonly used analytical research tool to identify and quantify these factors of the changes in emissions over time. In this study, five factors (population, CO_2 intensity, economic structure, consumption patterns and consumption volume) are selected to assess the changes in CO_2 emissions in China, using the SDA framework. The problem is formulated as depicted in Eq. 5-1.

$$\Delta \mathbf{CO_2} = \Delta \mathbf{pFLy_s y_v} + \mathbf{p}\Delta \mathbf{FLy_s y_v} + \mathbf{pF}\Delta \mathbf{Ly_s y_v} + \mathbf{pFL}\Delta \mathbf{y_s y_v} + \mathbf{pFLy_s}\Delta \mathbf{y_v} \qquad \text{Eq. 5-1}$$

Where,

Δ –represents the changes

P – is a scalar representing population

F – is the diagonalised CO_2 emission coefficient matrix

L – is the Leontief inverse matrix, $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$

$\mathbf{y_s}$ – is a column vector representing per capita consumption patterns

$\mathbf{y_v}$ – is a scalar representing the per capita consumption volume

Eq. 5-1 comprises five factors in total. Each term represents the contribution to a change in CO_2 emissions which are triggered by a single factor (i.e. driving force) while all the other factors are kept constant. The first factor represents population growth, **p**; the second factor represents the aggregated changes in the emission intensities (efficiency), **F**; the third factor represents changes in the production structure, **L**; the fourth factor represents changes in the consumption structure, $\mathbf{y_s}$; and the fifth factor represents changes in the consumption volume (GDP), $\mathbf{y_v}$. When performing the SDA, it is possible to compare terms relative to the start or end of each time-period, and this leads to a uniqueness problem. I average all possible first-order decompositions to avoid this problem (see Hoekstra and van der Bergh (2002)for a detailed discussion).

5.3.2 Data

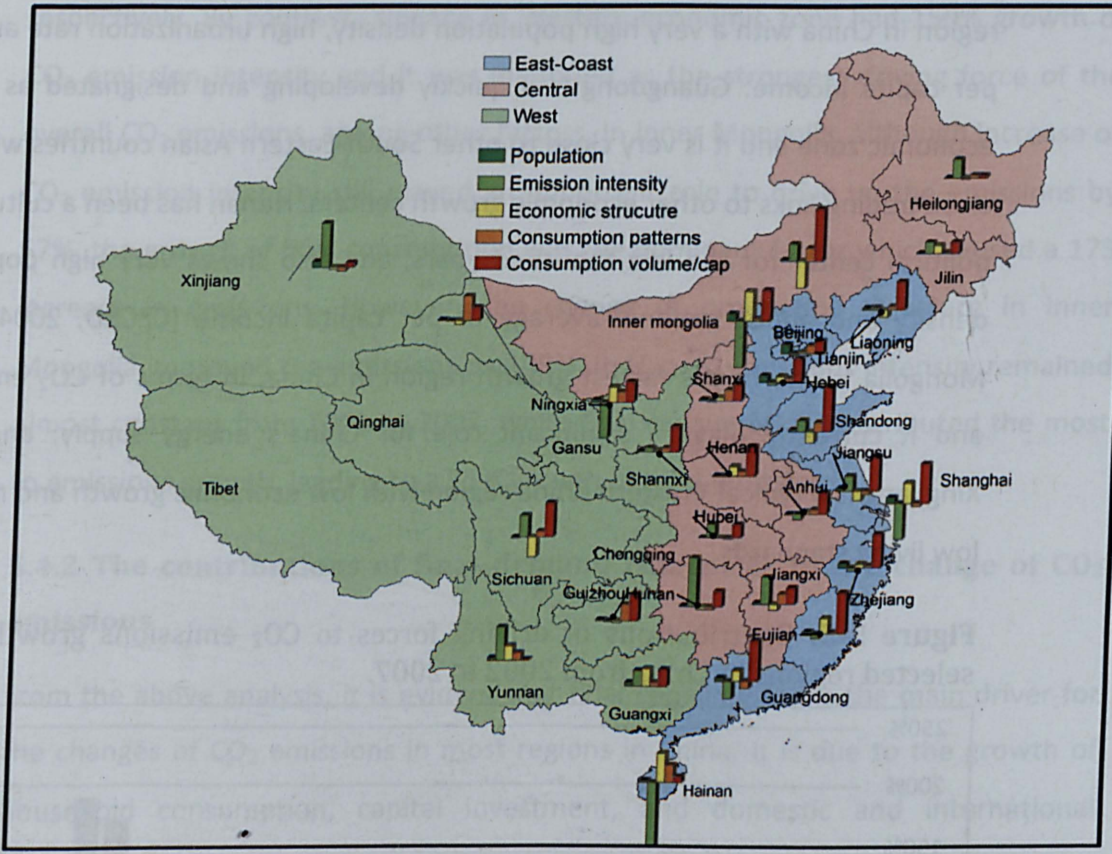
The 28 provincial IO tables for China in 2002 and 2007 are collected from Provincial Statistics Office of China. Although the IO tables are in an industry-by-industry format, the number of sectors varies considerably across different provincial IO tables. Due to this, to maintain consistency, I aggregate all the provincial IO tables into a consistent industry classification with 73 economic sectors and then converted the data into 2002 constant prices using the double deflation method(United Nations, 1999)based on the price data collected from China Provincial Statistics Yearbook 2008 (National Statistical Bureau of China, 2003-2008). The provincial IO tables for China include several categories of final demand - rural and urban households, government, capital formation, changes in inventories, domestic exports, international exports, domestic imports and international imports, which allows us to calculate the contributions of different final demand categories to the growth of CO_2 emissions. CO_2 emissions by sectors are calculated from combustion of fuels and industrial processes using the Intergovernmental Panel on Climate Change(IPCC) reference approach (IPCC, 1996). Energy data are collected from China Energy Statistical Yearbooks and China Provincial Statistical Yearbooks. In China provincial IO tables are by default based on the assumption that imports are produced with the domestic technology of the importing region, which is not very helpful for the analysis of the role of domestic driving forces in regional emissions growth. Thus, it is common practice to derive new requirements matrices and final demand vectors in which only domestic goods are included by removing imports from the IO data. A detailed explanation to this approach can be found in Weber *et al.* (2008).

5.4 Results

5.4.1 The contributions of different drivers to the changes in CO_2 emissions

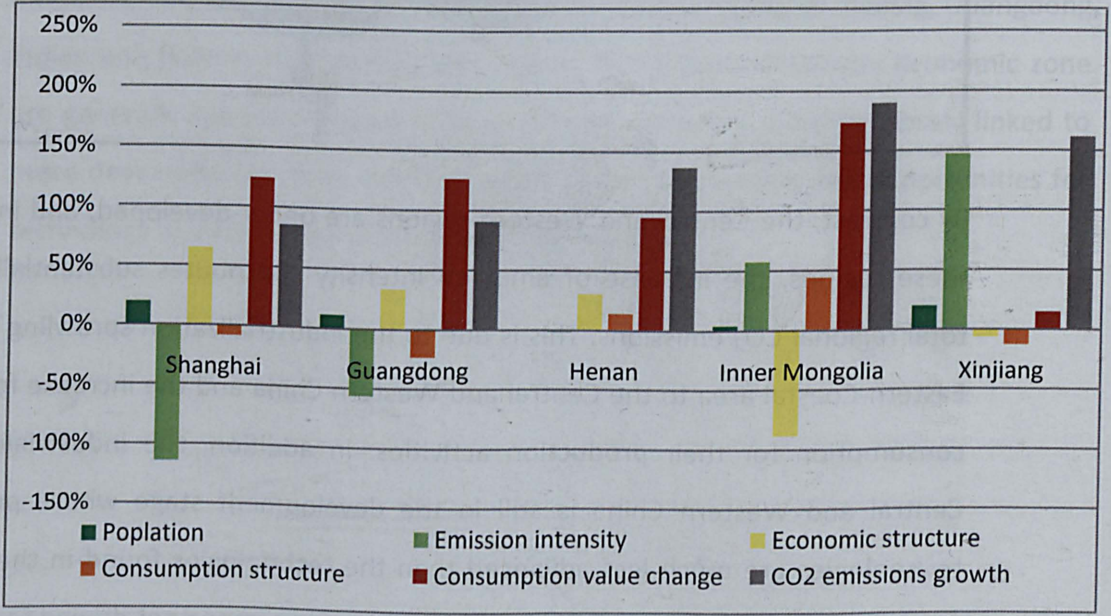
From 2002 to 2007, China's production-related CO_2 emissions more than doubled from 3440 Million Metric Tonnes (MMT) (Guan et al., 2008; Peters et al., 2007) to 6402 MMT. Overall, it is found that population has a relatively minor impact on CO_2 emissions in all the regions in China compared with other driving forces. It is due to the very low rate of population growth as a result of China's "One Child Policy" (average less than 1% per year between 2002 and 2007). Figure 5-4 shows that in the Eastern-Coastal economic zone, total final consumption is the main driver for the growth of CO_2 emissions compared with other four driving forces. Due to the fast improvement of production technology and associated energy efficiency, CO_2 emissions intensity decreased in some regions such as Shanghai, Beijing, Guangdong, Fujian and Hainan. It is because the regions in the Eastern-Coastal economic zone are generally more developed in terms of their economy which is closely linked to more developed countries and thus much higher investment and opportunities for technology and know-how transfer and innovation.

Figure 5-4: Drivers of change in CO_2 emissions in China from 2002 to 2007.



By contrast, the Central and Western regions are under-developed; and in most of these regions, the increase of emission intensity contributes substantially to the total regional CO_2 emissions. This is due to the industrialization sprawling from the Eastern-Coastal area to the Central and Western China and the increase fossil fuels consumption for their production activities. In addition, the industrialization in Central and Western China is still in the development stage where production technologies are much less advanced than the technologies found in the Eastern-Coastal economic zone. Total final consumption is an important driving force of CO_2 emission in many medium and lower income Central and Western regions such as Shanxi, Henan, Anhui, Jiangxi, Sichuan and Guizhou. A detailed analysis on the contribution of final consumption components is discussed in Section 5.4.2. In order to provide better insights into regional differences, five regions are selected for a detailed analysis: Shanghai (Eastern-Coastal), Guangdong, (Eastern-Coastal), Henan (Central), Inner Mongolia (Central) and Xinjiang (Western). These selected regions have very different attributes and development paths that make them interesting for this study: Shanghai as typical Eastern-Coastal region is the most developed region in China with a very high population density, high urbanization rate and high per capita income. Guangdong is a quickly developing and designated as special economic zone and it is very close to other South-Eastern Asian countries with very close trading links to other economic growth centers. Henan has been a cultural and political center for the last thousand years, and also shows very high population density and about national average of per capita income (CZCRD, 2004); Inner Mongolia is one of the fastest growth region in China, in terms of CO_2 emissions, and it currently plays a significant role for China's energy supply; and finally Xingjiang is a typical Western China region with low economic growth and relatively low living standards.

Figure 5-5: Contributions of driving forces to CO_2 emissions growth in five selected regions in China from 2002 to 2007.



From Figure 5-5, I can see that Shanghai and Guangdong, which are highly developed regions in China, enjoyed 'relatively' low emission growth rate, 86% and 90% respectively while the other three selected regions recorded an increase of 130% to190% of CO_2 emissions. In the more developed areas Shanghai and Guangdong, due to an improvement of emission intensity, shows a151 MMT (-114%) and 138 MMT (-56%) reduction of CO_2 emissions, respectively. However, these CO_2 reductions were more than compensated by the rapid growth of per capita GDP which led to an increase of 164 MMT (124%) and 309 MMT (126%) of CO_2 emissions, respectively. By contrast, Xinjiang in Western economic zone had 150% growth of CO_2 emission intensity and it was identified as the strongest driving force of the overall CO_2 emissions, among other factors. In Inner Mongolia, although increase of CO_2 emission intensity still played an important role to drive up the emissions by 57%, the growth of final consumption was the dominant factor which caused a 173% increase in emissions. However, the change of production structure in Inner Mongolia improved the emissions by 109%. In Henan, emissions intensity remained almost constant from 2002 to 2007, while final consumption contributed the most to emissions growth, leading to a 95% growth of total emissions.

5.4.2 The contributions of final demand categories to the change of CO_2 emissions

From the above analysis, it is evident that final consumption is the main driver for the changes of CO_2 emissions in most regions in China. It is due to the growth of household consumption, capital investment, and domestic and international exports. However, each region has its own economic characteristics and thus, influences exerted by final demand on CO_2 emissions may vary. For this reason, in this section, I further decompose the final demand into six components (Rural household consumption, urban household consumption, government expenditure, capital investment and changes of inventory, domestic export and international exports) in order to better understand the contributions of final consumption to the change of CO_2 emissions in different regions in China.

Table 5-1 shows the contributions of different final demand categories to the total change of CO_2 emissions in 28 Chinese regions, distinguished by three economic zones. From the table, I observe that international export contributed significantly to the changes of regional CO_2 emissions in the Eastern-Coastal economic zone except in Guangxi, Hainan and Hebei. All regions in the Eastern-Coastal economic zone showed significant growth in their domestic exports to other regions in China, and the contributions of their domestic exports to the total growth of CO_2 emissions were in the range of 16% to 114%. By contrast, in the Central economic zone, the impacts from international exports were rather minor, whereas urban household consumption, capital investment and export to other regions in China all had large contributions to the increase in emissions.

In the Western economic zone, the contributions from different final demand categories to the changes of CO_2 emissions varied due to the disparity of regional economic growth, economic characteristics and geographical locations. In Guizhou and Shannxi, domestic export contributed the most to the growth of their total regional CO_2 emissions by 106% for both regions. In Gansu and Ningxia, international export was the most significant contributor of CO_2 emissions due to their proximity to Mongolia and Russia. In Yunnan, capital investment led to a 63% growth of CO_2 emissions followed by urban (18%) and rural household consumptions (16%). However, in Sichuan, both domestic export and capital investment had large contributions to the CO_2 emissions increase. From Table 5-1, I can see that many regions in the Eastern-Coastal economic zone and some regions in the Central and Western economic zones showed a decrease in rural household consumption, which was due to the fast urbanization, that led to negative contributions to changes of regional CO_2 emissions.

Table 5-1: Changes of CO_2 emissions by different final demand categories in China, 2002-2007 (in %).

		Rural	Urban	Government	Capital + CIS	Domestic export	International export
East-Coast	Beijing	0	8	4	14	48	26
	Fujian	-3	18	2	18	42	24
	Guangdong	-3	13	-5	23	35	36
	Guangxi	1	10	2	43	39	5
	Hainan	19	17	-4	-27	114	-19
	Hebei	-4	4	2	-2	92	7
	Jiangsu	-2	3	-1	24	47	30
	Liaoning	0	6	-4	16	58	23
	Shandong	-1	11	6	34	16	35
	Shanghai	-2	-1	2	-5	55	50
	Tianjin	-9	6	0	6	61	36
	Zhejiang	1	12	1	30	25	30
Central	Anhui	-1	13	6	14	65	4
	Heilongjiang	5	16	10	26	41	2
	Henan	1	12	4	11	71	0

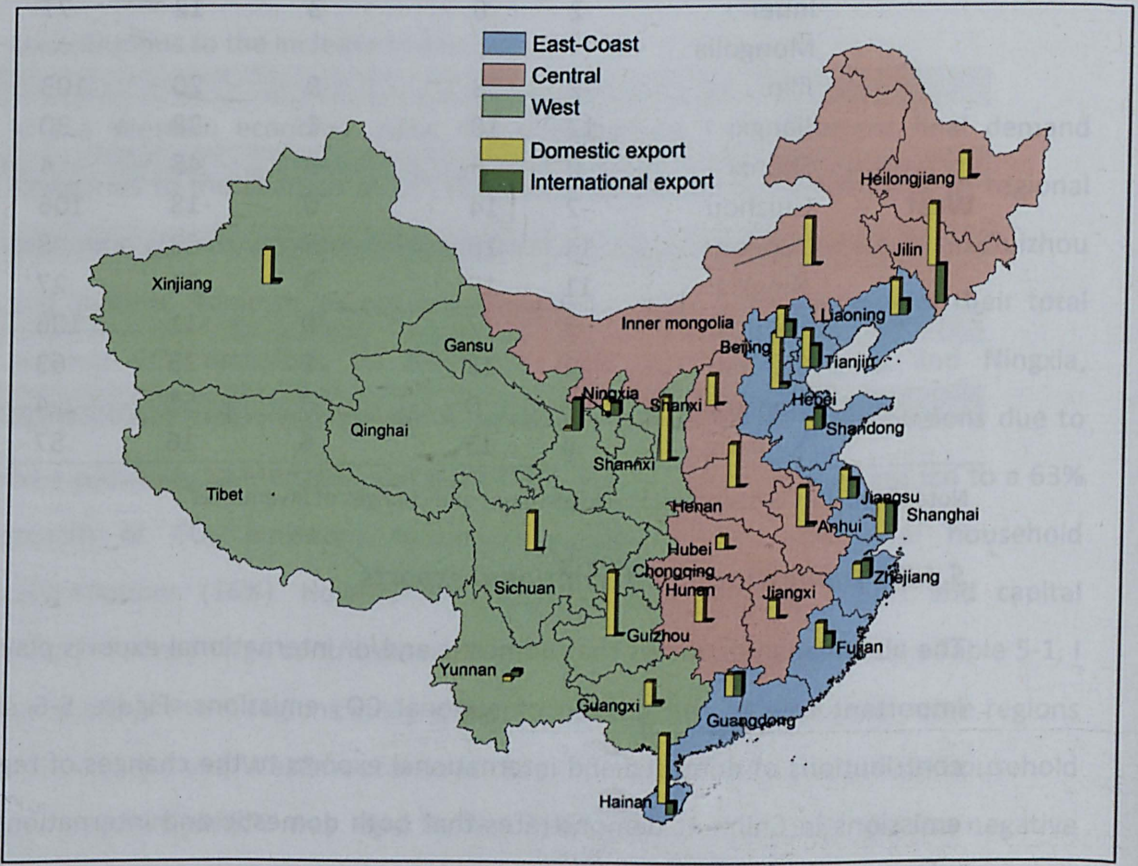
	Hubei	8	25	0	45	21	0
	Hunan	9	17	6	17	52	0
	Inner Mongolia	2	6	3	12	77	0
	Jilin	-2	33	9	20	103	-64
	Jiangxi	12	18	1	38	30	0
	Shanxi	0	5	-3	48	4	0
West	Guizhou	-2	14	0	-18	106	0
	Yunnan	14	18	3	63	-8	9
	Ningxia	11	17	3	21	27	21
	Shannxi	-2	7	0	-11	106	0
	Sichuan	-2	13	2	25	63	0
	Gansu	-3	0	-3	51	4	51
	Xinjiang	4	13	6	16	57	4

Note: Capital + CIS denote capital investment and changes of inventories

5.4.2.1 Domestic and international exports

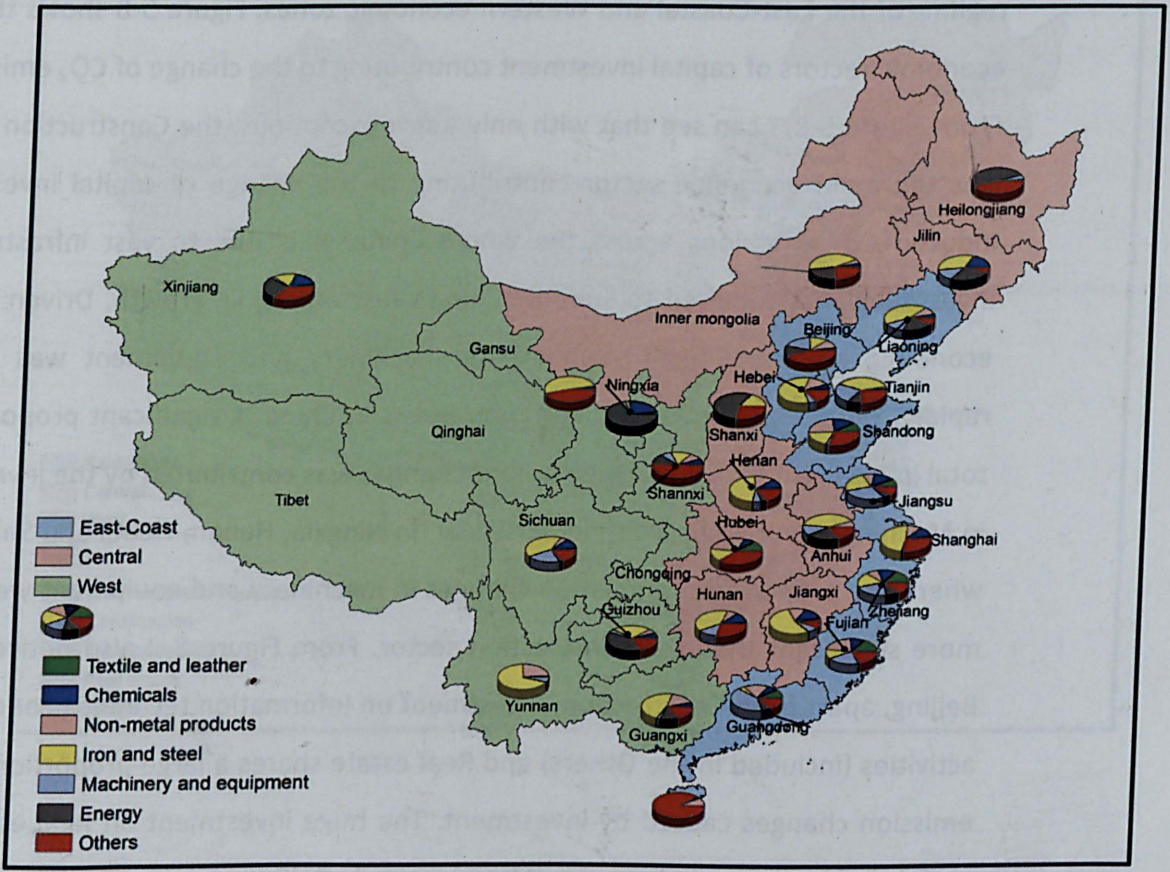
The above analysis shows that domestic and/or international exports played a very important role in the growth of regional CO_2 emissions. Figure 5-6 shows the contributions of domestic and international exports to the changes of regional CO_2 emissions in China. It demonstrates that both domestic and international exports were the major contributors of CO_2 emissions in most regions of the Eastern-Coastal economic zone, while only domestic export contributed significantly to the emission changes in the rest of China, apart from Gansu and Ningxia. Therefore, there is strong evidence that the Central and Western regions produced goods that were exported to the Eastern-Coastal regions and then the Eastern-Coastal regional used these goods to produce goods for domestic or international exports. Hence, the international export from the Eastern-Coastal regions not only caused a direct increase of CO_2 emissions in the Eastern-coastal area but also indirectly drove up the CO_2 emissions in the other regions in China.

Figure 5-6: Contributions of domestic and international exports to the changes of regional CO_2 emissions in China



To better understand the contribution of export to the changes of regional CO_2 emissions, I investigate the export for seven economic sectors (Textile and leather, Chemicals, Non-metal products, Iron and steel, Machinery and equipment, Energy, and Others). Figure 5-7 shows the proportions of contributions to the change of regional CO_2 emissions from different key exporting economic sectors. In this figure, I notice that in the Eastern-Coastal economic zone, the shares of export induced CO_2 emissions changes vary considerably in different exporting sectors. In Shanghai, Tianjin, Liaoning and Hebei, Iron and steel industry contributed the most to the exporting emissions changes, while all the other economic sectors together share about half of the changes of CO_2 emissions. In Guangdong and Jiangsu, exports of Machinery and equipment played a major role in export induced emissions changes. The shares are more equally distributed for different sectors in Zhejiang, and Fujian. In Shandong, Iron and steel, Non-metal products and Chemicals have contributed more than half of the total emissions growth, while Others contributed up to one third.

Figure 5-7: Key export sectors (both domestic and international) contributing to the change in CO_2 emissions in China

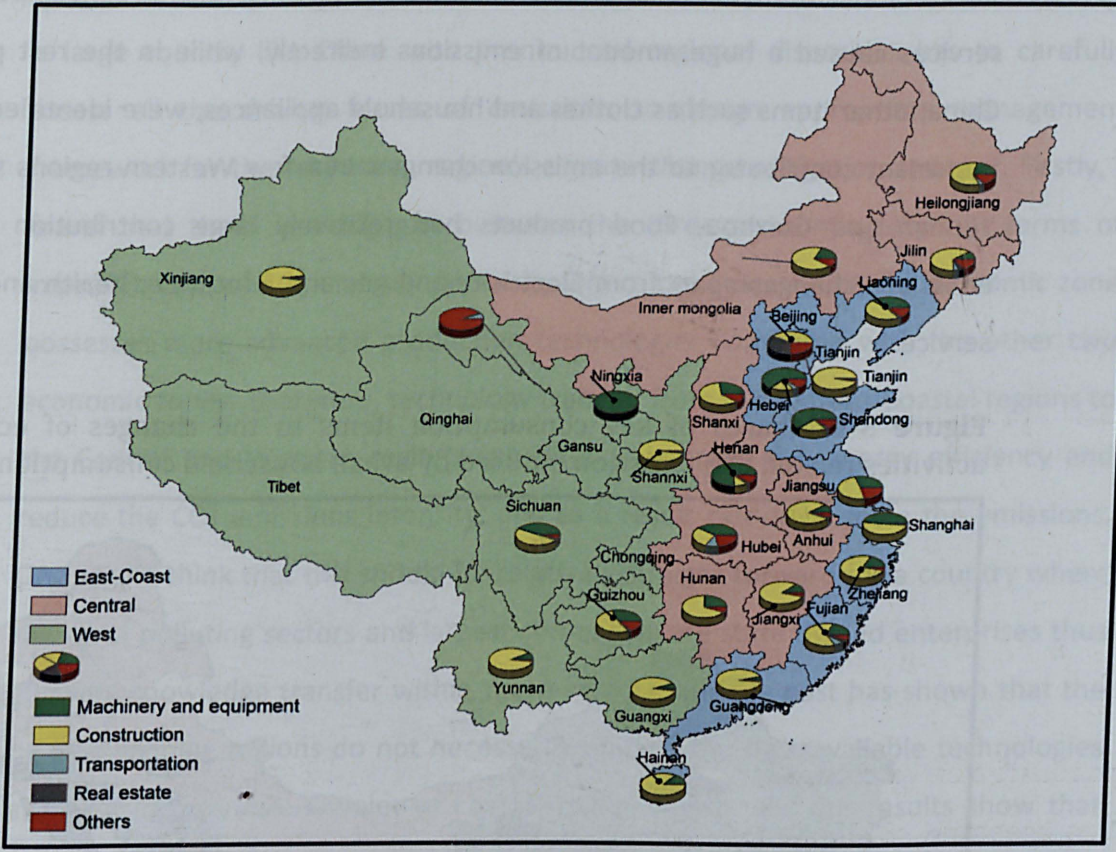


In the Central economic zone, Energy sector shared the largest proportion for the export induced emission changes in Heilongjiang and Shanxi due to the abundant coal reserves. These two regions together supply more than half of China's total coal consumption. In the rest of the Central economic zone, Iron and steel industry played a main role in inducing emission changes, except Hubei where the contributions from each economic sector are similar. Similar to the Central economic zone, Iron and steel and Energy industries were the major contributors of the changes of export induced emissions for most regions in the Western economic zone. The only exception is Ningxia where Chemicals accounted for one fourth of the total CO_2 emissions while Energy sector contributed to the rest of the emissions.

5.4.2.2 Capital Investment

With the fast growth of China's economy, capital investment causes a substantial amount of CO_2 emissions in all regions of the Central economic zone and several regions of the East-Coastal and Western economic zones. Figure 5-8 shows the key economic sectors of capital investment contributing to the change of CO_2 emissions. From Figure 5-8, I can see that with only a few exceptions, the Construction sector was the main economic sector contributing to the change of capital investment induced CO_2 emissions across the whole China. It is due to vast infrastructure investment was required to support China's fast economic growth. Driven by fast economic growth, China's demand for machinery and equipment was surging rapidly. Figure 5-8 shows that in most regions in China, a significant proportion of total investment induced CO_2 emissions changes was contributed by the investment in Machinery and equipment, in particular, in Ningxia, Henan, Hebei and Shandong, where the proportion of emission changes in machinery and equipment were even more significant than the construction sector. From Figure 8, I also notice that in Beijing, apart from Construction, investment on Information technology and related activities (included in the Others) and Real estate shares a large proportion of total emission changes caused by investment. The huge investment on Real estate was mainly led by the rapid increase of house price in Beijing.

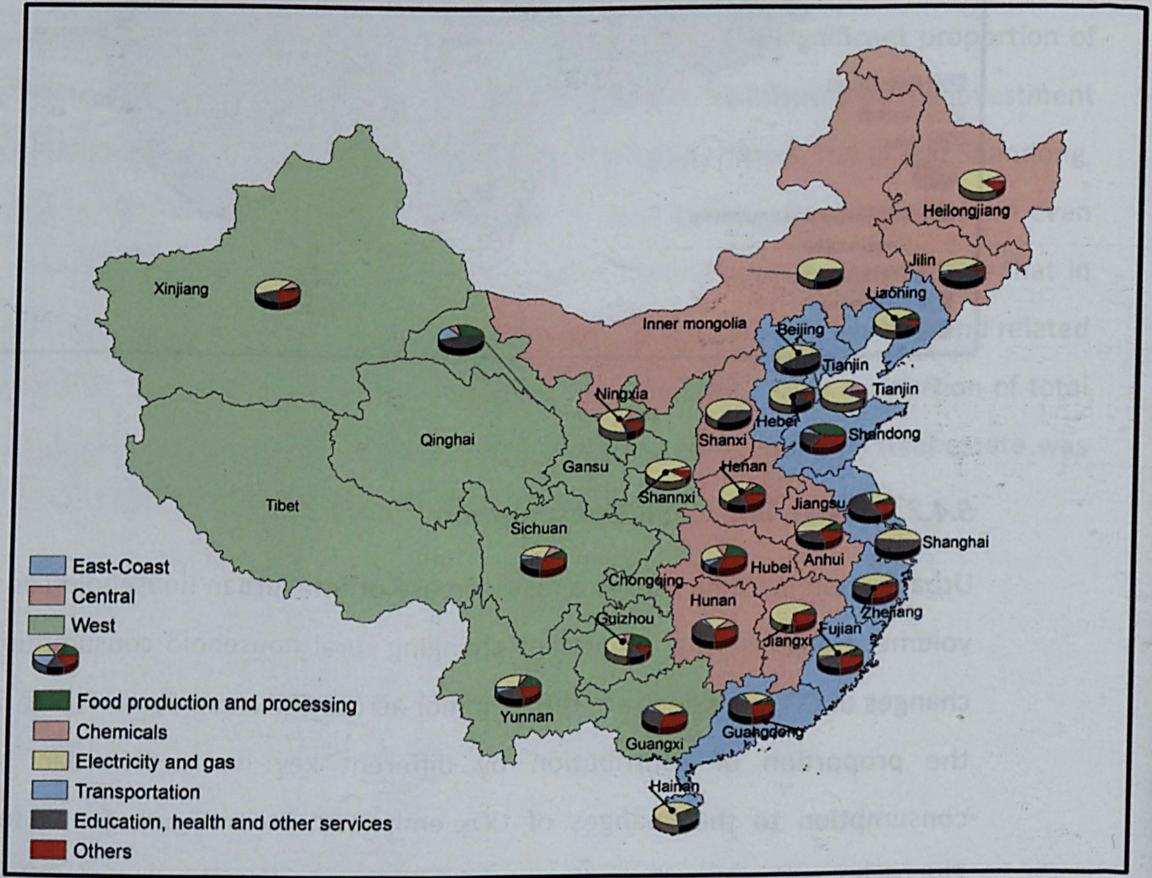
Figure 5-8: Key sectors for capital investment induced regional CO_2 emission changes



5.4.2.3 Urban household consumption

Urbanization in China causes a fast increase of total urban household consumption volume. However, the impacts of changing rural household consumption on the changes of CO_2 emissions are rather minor across China's regions. Figure 5-9 shows the proportion of contribution by different key items of urban household consumption to the changes of CO_2 emissions. From Figure 5-9, I found that Electricity and gas had significant contribution to the changes of CO_2 emissions because of rapid growth of directly using electrical appliances and indirectly through purchasing goods and services. However, in the more developed Eastern-Coastal economic zone, apart from Electricity and gas sector, services sectors such as Education, health and other services also played a significant role in affecting CO_2emissions(more than 30% for most of regions) due to higher people's living standards and accessibility to most public and private services. It also happened to many upper-medium income regions in the Central and Western economic zones, such as Inner Mongolia, Jilin and Shanxi that the fast increase of consumption on services caused a huge amount of emissions indirectly, while in the rest part of China, other items such as clothes and household appliances, were identified as an important contributor to the emission changes. In a few Western regions such as Yunnan and Guizhou, Food products had relatively large contribution to the emissions changes apart from Electricity and gas and Education, health and other services.

Figure 5-9: Shares of key consumption items to the changes of economic activities related CO_2 emission induced by urban household consumption



5.5 Discussion and conclusion

The fast growth of China's economy, urbanization, capital investment and export required a vast amount of energy and induced a large amount of CO_2 emissions. It is a big challenge for the Chinese government to reduce the speed of growth of CO_2

emissions without compromising economic growth as well as achieving the climate change mitigation targets with 40% reduction of carbon intensity by 2025. However, a large country like China with pronounced regional disparities has to carefully assess all the driving forces of emissions to design appropriate management framework for the respective region's climate change mitigation strategy. Firstly, I found that there is a big gap between the three economic zones in terms of improvements of CO_2 emission intensity where the Eastern-Coastal economic zone possesses more advanced production technologies compared with the other two economic zones. Therefore, technology transfer from the Eastern-Coastal regions to the Central and Western regions can directly improve the energy efficiency and reduce the CO_2 emissions intensity, and as a result can drive down the emissions. One would think that this should be relatively straight forward for a country where the most polluting sectors and largest companies are state owned enterprises thus allowing knowledge transfer within these sectors. But the past has shown that the new developing regions do not necessarily employ the best available technologies available in the more developed coastal regions. Secondly, our results show that export is one of the most important driving forces for the changes of CO_2 emissions. In particularly, domestic export in Central and Western China significantly contributes to the regional CO_2 emissions, which is partly driven by the international export in the East-Coastal regions. The economy in Eastern-Coastal regions benefits much from international export, while the emissions-intensive products, such as metal products and textiles are produced and imported from the Central and Western regions. To reduce emission intensity along the whole supply chain, regional government may need to coordinate and design inter-regional policies to increase the technology investment in the Central and Western regions from Eastern-Coastal regions. Thirdly, the fast increase in urbanization starting from the Eastern-Coastal area and followed by the Central and West of China causes a huge increase in emissions. Nowadays, urban households in China have more energy-intensive lifestyles. For example, it is not unusual for a family to have two or three televisions, and people often drive even though they can easily get access to the public transport(Hubacek et al., 2007). Reduction of household consumption on energy intensive goods and services may decrease both direct and indirect CO_2 emissions. It can be done through introducing green labels for energy efficient products. Last but not least, large capital investments on building infrastructures to support the fast economic growth in China also play an important role in affecting CO_2 emissions. In this study, I found that Construction was the largest contribution for the capital investment induced CO_2 emissions growth in most regions in China. Therefore, the investment should be focused on energy efficient buildings and other infrastructure in terms of long term energy saving. Overall, I conclude that only focusing on the driving forces at national level is not sufficient to achieve long term climate change mitigation targets, while there are significant regional differences. It is essential for China to design appropriate regional management framework for its mitigation strategies which also take regional socio-economic characterises into account.

Chapter 6 : Distributional Effects of Climate Change Taxation: The Case of the UK

The environmental input-output model can not only be used for assessing environmental impacts, but also investigate the distributional effects of environmental taxes on different segments of society. A spatial analysis of tax payment may show how different parts of a national or region would be affected and how this might affect "spatial inequality" in the absence of other compensation mechanisms. In this chapter, I assess and compare the distributional effects of a CO_2 tax vis-à-vis a multiple GHG tax on different income groups and lifestyle groups and analyse how the distributional effects of such taxes manifest themselves in space across the UK.

6.1 Introduction

The UK is one of few European countries that have already achieved their Kyoto Protocol targets over the 2008 to 2012 commitment period (UNFCCC, 1998)) and reduced greenhouse gas emissions by 17.6% below 1990 levels (ONS, 2009)). In addition, the UK has already set up legally binding reduction targets for a more ambitious long-term strategy and mitigation actions including "greenhouse gas emission reductions through actions in the UK and abroad of at least 80% by 2050, and reduction in CO_2 emissions of at least 26% by 2020, against a 1990 baseline" (Defra, 2008).

Taxes and emission trading schemes are both market-based policy instruments, which are frequently discussed in the climate change literature (EEA, 2006; European Commission, 2009; Garnaut, 2008). In an emission trading scheme the policy maker sets the amount of carbon to be traded and the price is determined through the market transactions. In a carbon tax scheme the policy maker sets the price for carbon and the amount of carbon emitted is dependent on the response (price elasticity) of producers and consumers, depending on availability of new technologies and their ability to use less carbon-intensive goods and services and a less carbon-intensive energy mix. I focus our analysis on carbon taxes though major parts of our discussion of the distributional impacts largely hold for both instruments. Proponents of carbon taxes highlight their simplicity and transparency (Mann, 2009; The Royal Society, 2002). Recently carbon taxation discussions in the UK have been reinforced by recommendations of the EU Commission (Grajewski, 2009) and the UK Royal Society (The Royal Society, 2002).

Apart from some notable exceptions (CCX, 2007; Whitehead, 2007) current economic instruments aimed at climate change mitigation focus mainly on CO_2 emissions (accounting for 77% of all global anthropogenic greenhouse gas (GHG) emissions in 2004) (Intergovernmental Panel on Climate Change (IPCC), 2007), but the Kyoto Protocol also refers to other GHGs (CH_4, N_2O, HFCs, PFCs and SF_6) as probably any follow-up climate change agreement will. From practical experience with CO_2 taxation it is well known that acceptability of a CO_2 or GHG tax is strongly influenced by its distributional impacts (Baranzini et al., 2000; Ekins, 1999; Kerkhof et al., 2008; Vermeend and Van der Vaart, 1998). However a number of studies suggest that carbon tax tend to be regressive in terms of distributional effects on income groups (e.g. Callan et al., 2009; Grainger and Kolstad, 2009; Hamilton and Cameron, 1994; Hassett et al., 2009; OECD, 1995; Speck, 1999; Wier et al., 2005)), i.e. households with lower income pay a larger share of their income on carbon tax payments than those with higher income. For example, a study for the USA by Hassett et al. (2009) shows that consumption of fuel and electricity drives the regressivity of the carbon tax. This potentially raises equity and fairness issues in a climate change debate where authors frequently highlight that those who are mostly responsible and who have the largest capacity to act should carry the majority of the costs (Baer et al., 2008; Commission on Growth and Development, 2008).

Nevertheless, the inclusion of non-CO2 GHG emissions in a multiple GHG tax provides alternative options to meet both socio-economic and environmental targets (Kerkhof et al., 2008). It is claimed that a multiple GHG tax policy can mitigate climate change with lower costs than a CO_2-only tax policy (Manne and

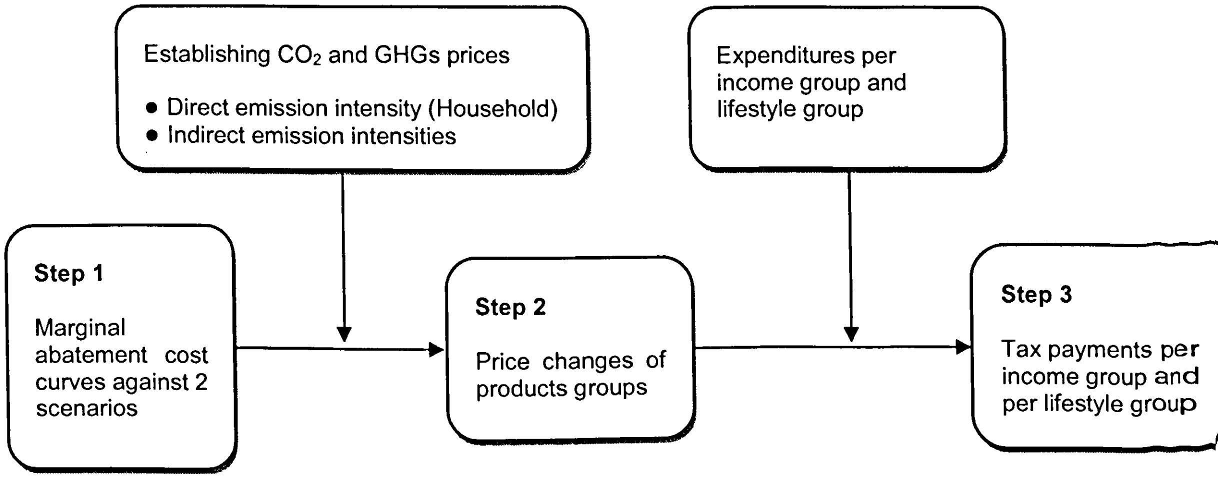
Richels, 2001; Weyant, 2006)), and that a multiple GHG tax can also decrease the regressive effects of traditional carbon taxation on the distribution of income (Kerkhof et al., 2008). On the other hand, in a GHG tax scenario the tax burden might be re-allocated differently across economic sectors, because a large amount of CH_4 and N_2O are emitted from agricultural processes whereas CO_2 emissions are mostly generated by fossil fuels combustion in industry, energy supply and transport (ONS, 2006b). This may alter the distribution of the tax burden across consumers because of different consumption patterns.

This chapter aims to assess and compare the distributional effects of a CO_2 tax vis-à-vis a multiple GHG tax on different segments of society in the UK. In addition, in this study I analyse how the distributional effects of such taxes manifest themselves in space across the UK by using geo-demographic data. A spatially explicit analysis of tax payment per income and lifestyle group shows how different parts of the UK would be affected and how this might affect "spatial inequality" in the absence of other compensation mechanisms.

6.2 Methods

In order to assess and compare the distributional effects of a multi-GHG tax with a CO_2 tax, I estimate the direct and indirect tax payments of UK households for different income and lifestyle groups adopting similar approaches used by Kerkhof et al. (2008)) and Wier et al.(Wier et al., 2005). I carry out the analysis in 3 steps (see Figure 6-1): Firstly, we determine hypothetical tax rates for a GHG tax and a CO_2 tax, respectively, for different carbon reduction levels. Secondly, I estimate the price changes for different consumption items induced by a GHG and CO_2 tax, respectively. This is achieved by linking the respective tax rates to an environmentally extended input–output model, which allows us to quantify the tax implications based on embodied carbon in consumer products taking account of the whole domestic supply chain. Finally, I couple the price changes for different consumption categories with geo-demographic and household expenditure data to quantify the tax payments per income group and per lifestyle group in the UK.

Figure 6-1: Steps to measure CO2 and GHGs tax payments



6.2.1 Establishing tax rates

In the absence of a comprehensive GHG or CO_2 tax in the UK, I establish hypothetical tax rates in this study. The rates are determined by applying marginal abatement cost data from the UK Climate Change Committee (Committee on Climate Change, 2008)) to the UK emission reduction target with an ambitious 30-percent reduction by 2020 compared to 1990 CO_2 equivalent The abatement cost curves are constructed based on information for the following sectors: agriculture, industry, domestic construction, non-domestic construction, transport, and waste treatment. Based on this information the cost curves were established by ranking emission reduction measures according to their cost-effectiveness. Marginal abatement cost curves are a key tool in environmental economics linking emission reductions and their incremental cost and have become central to the economic assessment of mitigation strategies (McKitrick, 1999)). This approach does not try to optimize economic output, but provides a method to implement policy objectives at least-cost (Baumol and Oates, 1971) Under a multiple GHG strategy, the mitigation of different Kyoto gases are interchangeable for achieving UK's reduction target in CO_2 equivalents; thus compared to a single gas (CO2) strategy, the abatement cost curve in this case includes additional reduction options associated with the other gases.

6.2.2 Tax induced price changes

A GHG or CO_2 tax imposed on industries and households in the UK will change the price of products. To examine these price changes, I use input-output analysis to quantify both direct and indirect effects of CO_2 and GHG taxes for a product accounting for all emissions throughout the domestic supply chain. For example, direct emissions from driving a car are due to the combustion of petrol while indirect emissions from buying the car arise through the production process of the car and all its inputs. Therefore, in the first case, taxes are imposed on the emissions related to the consumption of the product (direct effect), while in the second case, taxes are imposed upon the industry responsible for the emissions due to the production of the product (indirect effect). In line with other studies I assume that taxes imposed on industry sectors are fully passed on to the consumer. In order to be able to use consumer expenditure data I need to assume that the purchasing power of consumers across the income groups stays the same (e.g. through some subsidy scheme) (Kerkhof et al., 2008)).

The total price change of consumption category *k* is the sum of direct and indirect price changes:

$$\Delta p_k^{tot} = \Delta p_k^{dir} + \Delta p_k^{ind} \qquad \text{Eq. 6-1}$$

Where Δp_k^{tot} is the total price change of consumption category *k*, Δp_k^{dir} is the direct price change of consumption category *k*, and Δp_k^{ind}, is the indirect price change of consumption category *K*.

Direct price changes are the result of taxation of direct household GHG or CO_2 emissions. The price change after taxation of direct emission of consumption category *k* is shown in Eq. 6-2:

$$\Delta p_k^{dir} = f_k^{dir} t \qquad \text{Eq. 6-2}$$

Where f_k^{dir} indicates the direct emission intensity of consumption category *k* (ton CO_2 equivalent of GHG or CO_2 emitted per pound of product output) and *t* is the tax rate of a comprehensive GHG tax or CO_2 tax.

Indirect price changes are the result of taxation of emissions that are emitted from industry sectors. Eq. 6-3 denotes the direct tax payments per unit of output in industry sector *j*:

$$d_j = f_j t \qquad \text{Eq. 6-3}$$

where f_j is the emission intensity of sector *j*, and *t* the tax rate.

I calculate the total tax payments of industry sectors by input-output analysis, and then I obtain total indirect price changes of consumption categories through linking the supply industries to final consumption categories. This is represented in the Eq. 6-4:

$$\Delta p^{ind} = d(I - A)^{-1}C \qquad \text{Eq. 6-4}$$

where Δp^{ind} is a row vector containing the indirect price changes of consumption categories; d is a row vector of emission tax payments per unit of sectoral output; $(I - A)^{-1}$ is the Leontief inverse matrix (Leontief, 1986)). Here, C is a sector-COICOP transition matrix indicating the supply of the UK-based production sectors of consumption items bought by UK consumers. The coefficients in the transition matrix are expressed as the supply of a sector to a product group divided by the total industrial supply to that product group.

6.2.3 Distributional effects

The tax payments of households in different income groups and lifestyle groups are a result of the price increase for different consumption items and the specific basket of goods and services different income groups and lifestyle groups consume. Consequently, the total tax payment of a certain income group or lifestyle group can be calculated by the sum of the total price increase for each consumption category times the total expenditure of a certain income group or lifestyle group on each consumption category, as shown in Eq. 6-5.

$$v_g = \sum_k \Delta p_k^{tot} e_{k,g} \qquad \text{Eq. 6-5}$$

Where $e_{k,g}$ is the total annual expenditure of income group *g* for consumption category *k*.

6.2.4 Data

Marginal cost curve estimates are taken from the Climate Change Committee (Committee on Climate Change, 2009) to impute emission reductions for different sectors. Data on greenhouse gas emissions of industry sectors are published by the UK Office for National Statistics (ONS, 2006b). Input-output tables for the UK economy are provided by the Stockholm Environment Institute, York (Wiedmann et al., 2008). Consumer expenditures per income group are taken from the Family Expenditure Survey (ONS, 2006a), and expenditures per lifestyle group are from the MOSAIC database (Harris et al., 2005).

MOSAIC is a commercial geo-demographic market segmentation system, which classifies all consumers in the UK according to 11 neighbourhood groups and 61 neighbourhood types (full description in Appendix Two), which can be interpreted as lifestyles (see (Experian, 2008)). The MOSAIC lifestyle profiles are mainly based on census data which is augmented with a variety of other data sources including expenditure and income information, electoral roll, Experian lifestyle survey information, and consumer credit activities, alongside the post office address file, shareholders register, house prices and council tax information, and ONS local area statistics (see (Experian, 2008)).

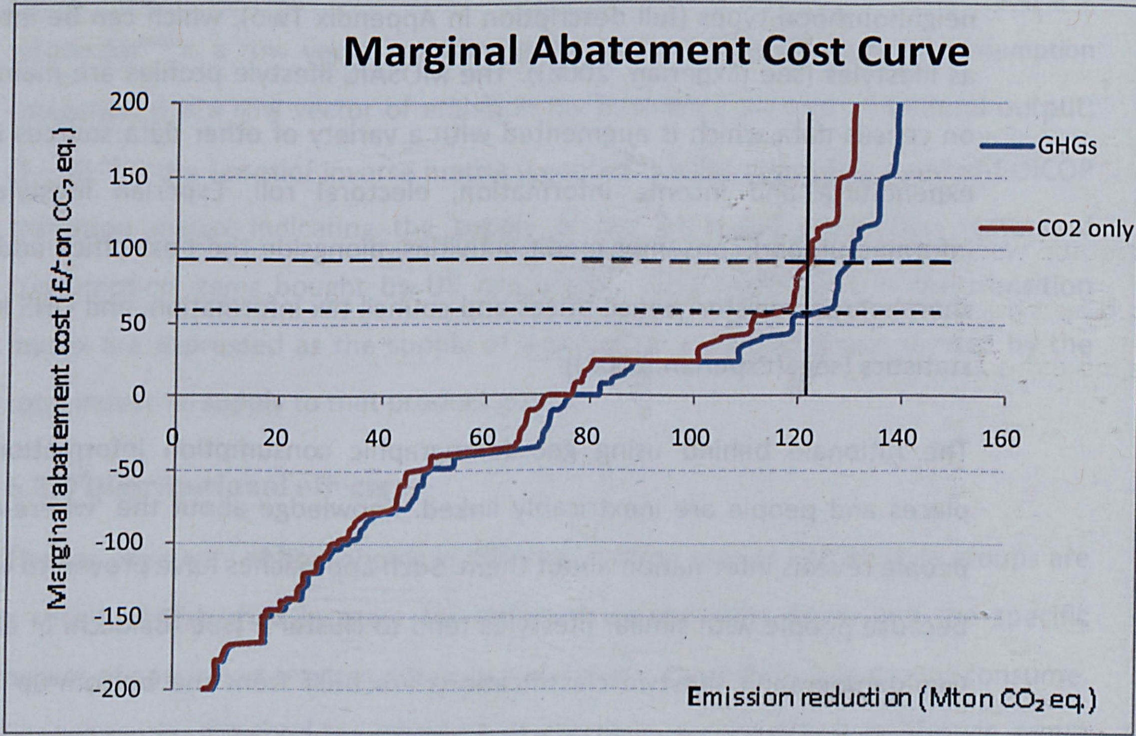
The rationale behind using geo-demographic consumption information is that places and people are inextricably linked. Knowledge about the 'where-about' of people reveals information about them. Such approaches have proven to work well, because people with similar lifestyles tend to cluster – (see (Baiocchi et al., 2010)). Geo-demographic lifestyle classifications are built from the bottom-up based on spatially specific variables covering characteristics of both people and places (Baiocchi et al., 2010). Hence, the introduction of this type of data does not only allow the extension of the analysis `into space', but also ultimately the establishment of links between consumption, lifestyles and the physical environment in which activities are taking place.

6.3 Results and Discussion

6.3.1 Tax rate and cost-effectiveness

The abatement cost curves shows quantitatively the most cost-effective options to achieve emission reduction targets and the associated costs across sectors. Both abatement cost curves for various GHGs and CO_2 are shown in Figure 6-2. It appears that the marginal abatement costs of all GHGs are much lower than the marginal cost of a reduction of CO_2 emissions. Therefore, the mitigation of a comprehensive GHG strategy provides relatively cheaper abatement options compared to a CO_2 reduction strategy alone.

Figure 6-2: Tax rates result from intersection of marginal abatement cost curves and the UK emission reduction targets by 2020



Note: the red line represents the abatement cost of CO_2 emissions and the blue line indicates the abatement cost of GHG emissions. The parts of the curves under the x axis show negative abatement cost or positive net present values (3.5 % discount rate), i.e. over the lifetime of the technology it saves more than it costs.

The optimal tax rates for a comprehensive GHG and a CO_2 tax are established through the intersection of the abatement cost curves with the respective UK climate change target. The GHG tax rate would be about 56 pounds per ton CO_2 eq.

and 93 pounds per ton CO_2 eq. for the CO_2 tax in order to achieve a 122 million tons CO_2 eq. emission reduction (see Figure 6-2). The steep slope of the marginal abatement curve for both comprehensive GHG and CO_2 shows that further incremental emission reductions would lead to a considerable tax increases. Thus, I would expect the problems of acceptability associated with a carbon tax to become more and more prominent. On the other hand, the more stringent the target gets, the better a GHG tax performs against CO_2 tax.

6.3.2 Price changes

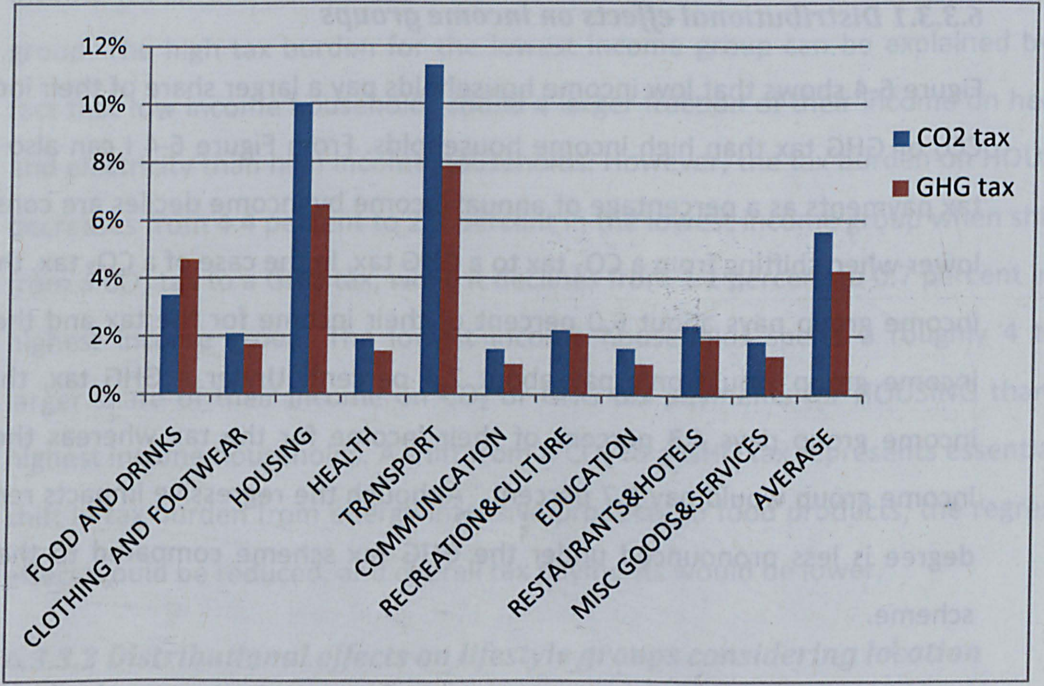
In general, consumption categories taxed with the CO_2 tax show higher price increases than the same category with a GHG tax because the CO_2 tax rate is higher than the GHG tax rate to achieve the same climate change mitigation target. However, for some consumption categories the results are reversed. For example, MEAT, FRUIT AND VEGETABLES cause high emission of methane and N_2O due to enteric fermentation by cows and de-nitrification processes in soils which are ignored under a CO_2 tax scheme and instead taxed under the GHG tax scheme. In addition, WATER SUPPLY shows a higher price increase under the GHG tax than the CO_2 tax due to the production of N_2O during nitrogen removal from domestic wastewater.

Table 6-1: Top ten consumption products with the highest price changes after CO_2 and GHG taxation

	Consumption categories	CO2 tax	Consumption categories	GHG tax
1	GAS & OTHER FUELS	102.8	GAS & OTHER FUELS	65.3
2	ELECTRICITY	77.3	ELECTRICITY	48.2
3	OPERATION OF PERSONAL TRANSPORT EQUIPMENT	18.5	OPERATION OF PERSONAL TRANSPORT EQUIPMENT	11.3
4	TRANSPORT SERVICES	13.9	MEAT EXCL POULTRY	9.0
5	MEAT EXCL POULTRY	4.4	TRANSPORT SERVICES	8.6
6	POULTRY MEAT	4.2	WATER SUPPLY	7.9
7	WATER SUPPLY	4.0	POULTRY MEAT	6.8
8	VEGTABLE AND ANIMAL OILS	4.0	FRUIT AND VEG	6.5
9	FRUIT AND VEGETABLE	3.7	GRAIN PRODUCTS	5.9
10	GRAIN PRODUCTS	3.7	DAIRY PRODUCTS	4.7

The GHG tax and CO_2 tax lead to different distributions of the tax burden across consumption categories. The most affected sectors in both categories are ELECTRICITY and GAS & OTHER FUELS with considerable price increases. The high price changes of these two product groups result from their high CO_2 emission intensities. For example, GAS AND OTHER FUELS is the most affected consumption category with a doubling in prices; high levels of CO_2 emissions in this category are caused, for instance, by cooking and heating. The next most affected category is ELECTRICITY where a large amount of CO_2 emissions is created during the production process through burning fossil fuels. The price changes for OPERATION OF PERSONAL TRANSPORT EQUIPMENT and TRANSPORT SERVICES are also large with 18.5 percent and 13.9 percent, respectively, due to combustion of gasoline and associated emissions.

Figure 6-3: Price changes after CO2 and GHG taxation for ten aggregate consumption categories



An overview of the price changes across 10 aggregate consumption categories are provided in Figure 6-3. (For a detailed description of 10 aggregate consumption categories see Table 6-1). The results show an average price increase across all consumption categories of 5.6 percent under a CO_2 tax and 4.3 percent under the GHG tax. The average price increase of consumption categories in GHG strategy is therefore 1.3 percentage point lower for the same environmental gain. When shifting from a CO_2 to a GHG tax the price increase for HOUSING and TRANSPORT would drop by 3.5 percentage points while the one for FOOD AND DRINKS would increase by 1.3 percentage points. In addition, the price increases for other consumption categories, such as CLOTHING AND FOOTWEAR, HEALTH, and EDUCATION would drop by approximately 0.5 percentage points when taxing CO_2 rather than GHG.

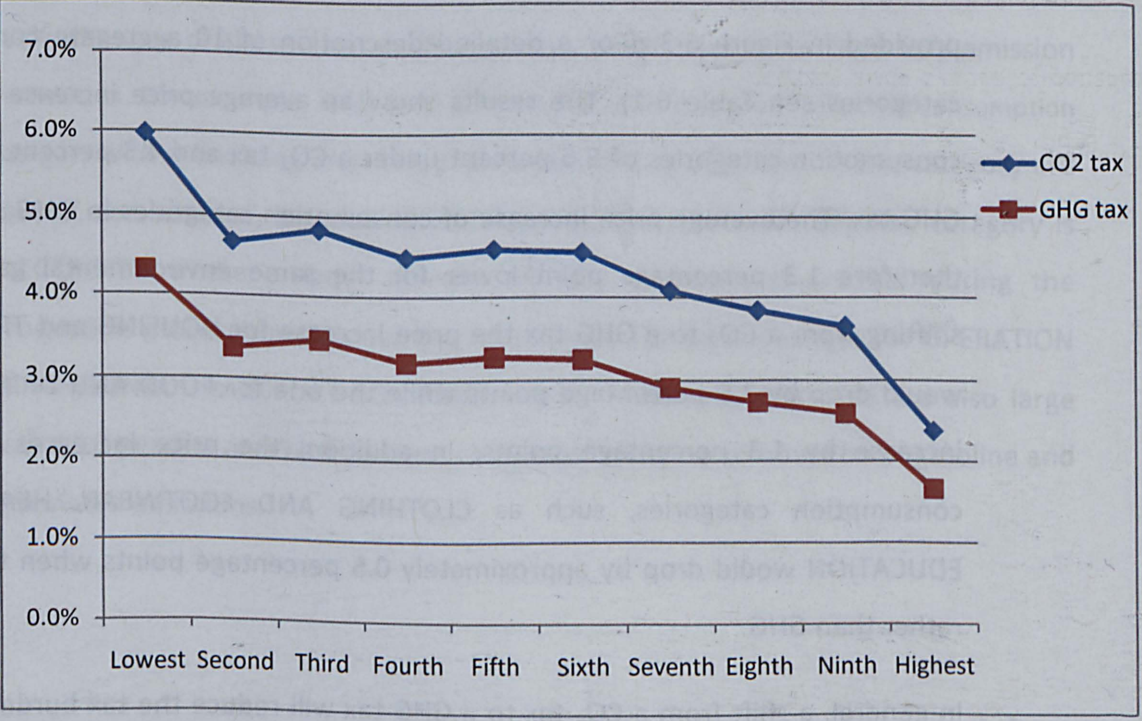
In general, a shift from a CO_2 tax to a GHG tax will reduce the tax burden and will spread the burden differently across consumption categories, such as decreasing the load on energy-intensive products and increasing payments on food products.

6.3.3 Distribution of tax burdens

6.3.3.1 Distributional effects on income groups

Figure 6-4 shows that low income households pay a larger share of their income for CO_2 or GHG tax than high income households. From Figure 6-4 I can also see that tax payments as a percentage of annual income by income deciles are considerably lower when shifting from a CO_2 tax to a GHG tax. In the case of a CO_2 tax, the lowest income group pays about 6.0 percent of their income for the tax and the highest income group would only pay about 2.4 percent. Under a GHG tax, the lowest income group pays 4.3 percent of their income for the tax whereas the highest income group would pay 1.7 percent. Although the regressive impacts remain, the degree is less pronounced under the GHG tax scheme compared to the CO_2 tax scheme.

Figure 6-4: Tax payment as percentage of income by income deciles in the UK (£93/ton CO_2 eq. for CO_2 tax and £56/ton CO_2 eq. for GHG tax).



The CO_2 and GHG tax payments for different consumption categories by low, medium and high income groups are shown in Figures 6-4. The figure shows that the regressivity of a CO_2 tax is caused by the high tax burden on HOUSING, which contains most of tax payments on electricity and gas. The CO_2 tax payments for

HOUSING contribute more than 70 percent of total tax payments in the lowest income group and about 40 percent of total tax payment in the highest income group. The high tax burden for the lowest income group can be explained by the fact that low income households spend a larger fraction of their income on heating and electricity than high income households. However, the tax burden on HOUSING decreases from 4.4 percent to 2.9 percent in the lowest income group when shifting from a CO_2 tax to a GHG tax, while it declines from 1.1 percent to 0.7 percent in the highest income group. The lowest income households spend a roughly 4 times larger share of their income on CO_2 or GHG tax payments for HOUSING than the highest income households. A shift from a CO_2 to a GHG tax represents essentially a shift in tax burden from energy intensive products to food products; the regressive effect would be reduced, and overall tax payments would be lower.

6.3.3.2 Distributional effects on lifestyle groups considering location

Apart from income groups, I also apply the model to lifestyle groups using a geo-demographic database of consumption activities. Lifestyle groups are not only classified by income, but also by various other social-economic factors as well as the physical environment. People belonging to different lifestyle groups have different consumption patterns and thus differences in carbon emissions. The detailed description of each lifestyle group (e.g. Symbols of Success, Welfare Borderline, Municipal Dependency, *etc.*) can be found in Appendix Two. Moreover, the spatial context they live in partially determines the extent to how difficult they can respond to price changes. Therefore, the effects of carbon taxes and what these would mean for different lifestyle groups would be very different.

Figure 6-5: Tax payments as percentage of annual income, differentiated between ten aggregate consumption categories, by lowest, medium and highest income groups.

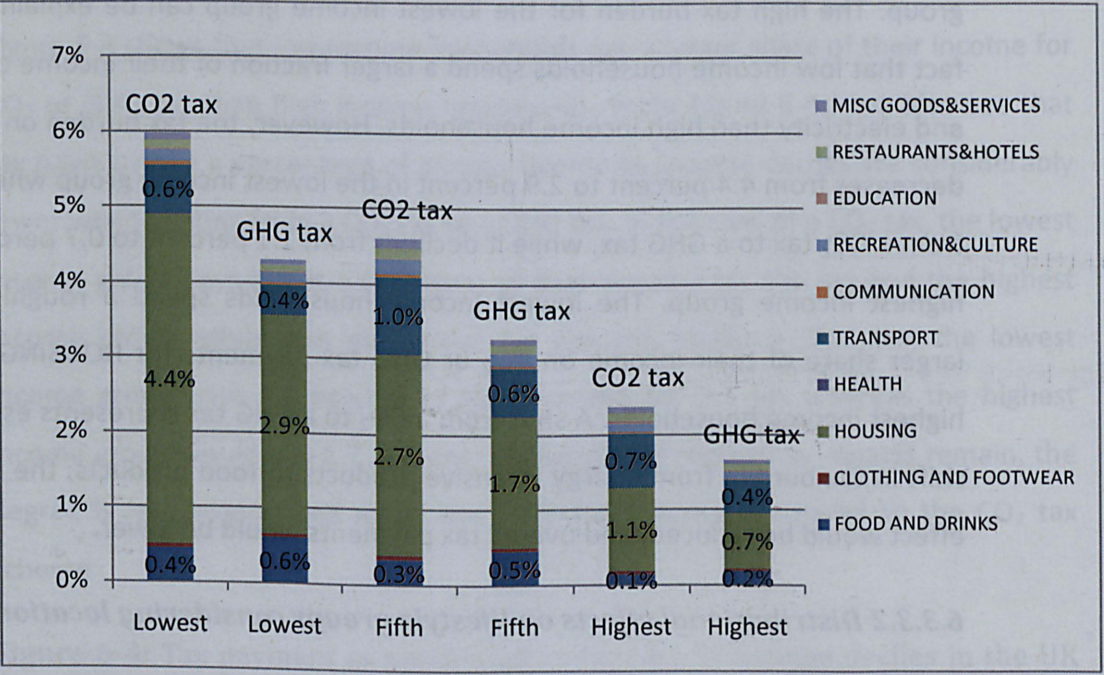


Figure 6-6 shows GHG tax and CO_2 tax payments as a percentage of income per lifestyle groups. The lower income lifestyle groups such as Welfare Borderline, Municipal Dependency, and Blue Collar Enterprise[6] pay a greater share of their income to a CO_2 tax and a GHG tax than lifestyle groups with high living standards such as Symbols of Success and Happy Families. Symbols of Success would pay slightly less than 5 percent of their income on a CO2 and 3.3 percent on a GHG tax, while Municipal Dependency would pay more than 7 percent of their income under a CO_2 and 5 percent under a GHG tax. Across groups I see that a GHG tax is distributed more equally than a CO_2 tax.

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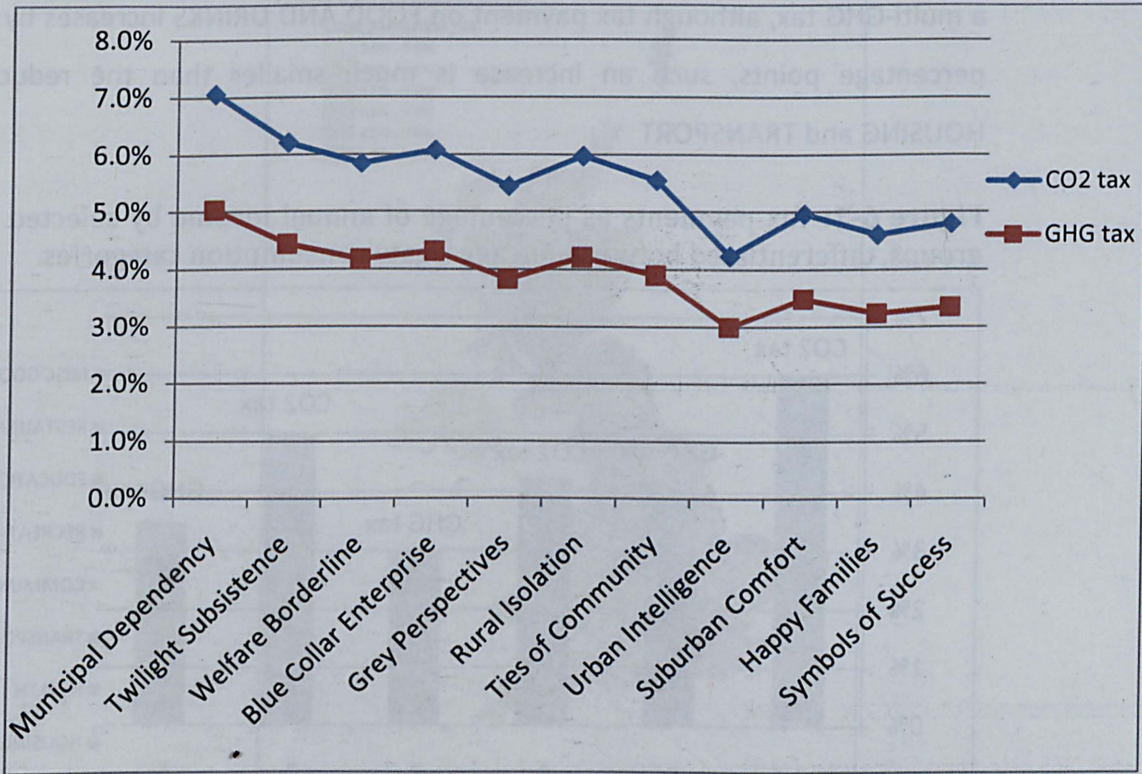
[6] For a complete list and description of lifestyle groups see (http://guides.business-strategies.co.uk/mosaicuk/html/main/animation.hta and a summary in the Supporting Information).

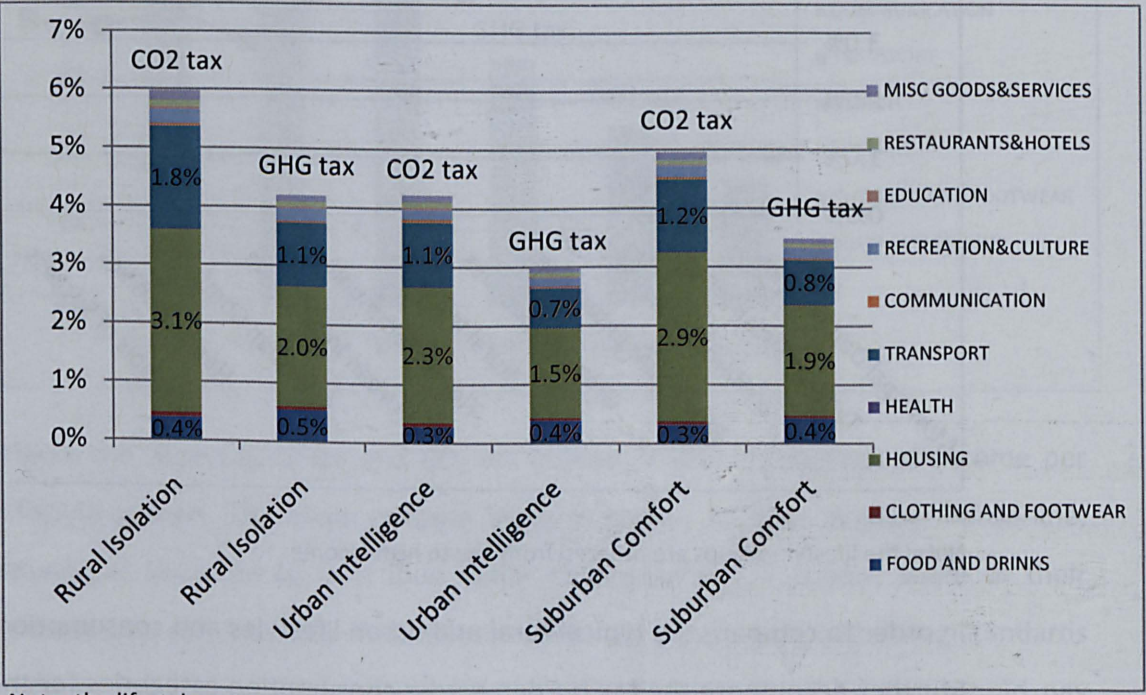
Figure 6-6: Tax payment as percentage share of annual income by lifestyle group in the UK in 2004, in an order from the poorest group to the richest group (£93/ton CO_2 eq. for CO_2 tax and £56/ton CO_2 eq. for GHG tax).



Note: the lifestyle groups are ordered from low to high income

In order to compare the typical rural and urban lifestyles and consumption patterns I further decompose the tax burden across consumption categories for the lifestyle groups Urban Intelligence, Suburban Comfort, and Rural Isolation (see Figure 6-6). It shows that there is still inequality of a CO_2 or GHG tax burden across lifestyle groups from urban to suburban and rural areas. Rural Isolation households pay a much higher share of their income for a CO_2 and GHG tax than Suburban Comfort households (about 0.8 percentage points higher) and Urban Intelligence Households (about 1.7 percentage points higher). This can be explained by the high tax burden on HOUSING (48 Percent of total tax payment) and TRANSPORT (26 percent of total tax payment) due to their relatively high demand for heating, electricity and transport. Urban Intelligence and Suburban Comfort households have fairly easy access to public transport services compared to Rural Isolation households. When shifting from a CO_2 tax to a multi-GHG tax the tax burden for HOUSING and TRANSPORT decreases significantly, especially for the Rural Isolation group leading to a more equal distribution of the tax burden across lifestyle groups (see Figure 6-7). Rural Isolation households pay 30 percent less tax through shifting from a CO_2 to a multi-GHG tax, although tax payment on FOOD AND DRINKS increases by about 1 percentage points, such an increase is much smaller than the reduction on HOUSING and TRANSPORT

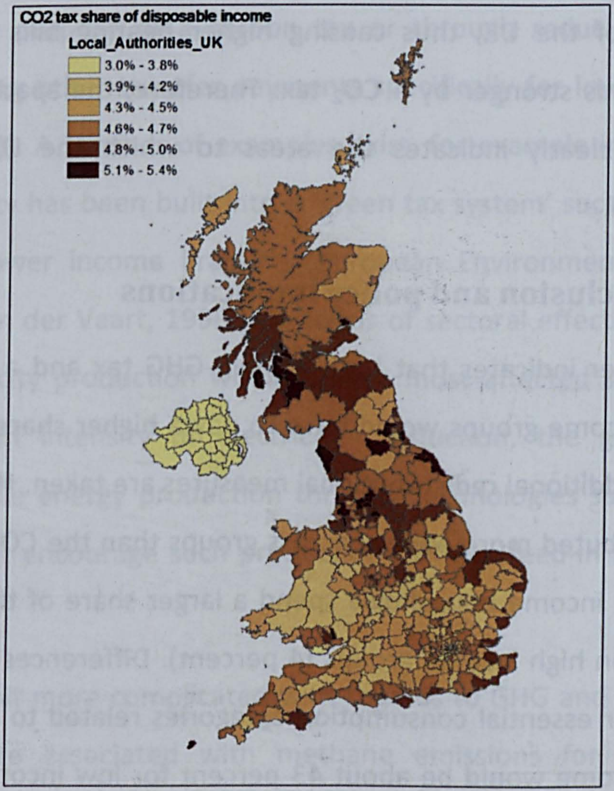
Figure 6-7: Tax payments as percentage of annual income by selected lifestyle groups, differentiated between ten aggregate consumption categories.



Note: the lifestyle groups are ordered from low to high income

Crucially for the analysis of the effects of a CO_2 or GHG tax, consumers have different abilities to respond to the tax and change their behavior due to various socio-economic factors, location, and the availability of infrastructure. Lifestyle groups such as `Suburban Comfort' or `Rural Isolation', for example, are much more dependent on their cars than households grouped under `Urban Intelligence' and are hit much harder by increased fuel prices. Households in the lifestyle groups `Welfare Borderline' and `Municipal Dependency' have much fewer options to react to increased costs for operating their houses than `Symbols of Success', because they often do not own the houses they live in and often do not have the means to undertake larger retro-fitting exercises.

Figure 6-8: CO_2 tax share of disposable income across 434 local authorities in the UK



Because our data is spatially referenced, i.e. I know where people of different lifestyle types live; I can also analyse how parts of the UK are affected differently by the tax. Even though I will restrict myself to a short demonstration of results rather a complete analysis in order to conserve space, there are a variety of analytical options, which I will leave to future research. Figure 6-8 shows CO_2 tax shares of disposable income across 434 local authorities[7](Defra, 2006)) in the UK. Local authorities in North England and Scotland would be affected most by a CO_2 tax, and the average CO_2 tax share of disposable income is more than 4.5 percent in these two regions. This is mainly driven by the fact that particularly poor lifestyle groups – often depending on usually badly insulated council houses - such as Welfare Borderline, Municipal Dependency and Twilight Subsistence make a large share of the population. Moreover, these regions show a higher proportion of rural lifestyles (e.g. `Rural Isolation'); peoples' homes tend to be further away from the working

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[7] Local authority is local government in the United Kingdom. In total, there are 434 local authorities in the UK. 354 of these are in England, 26 in Northern Ireland, 32 in Scotland and 22 are in Wales.

place, shops, pubs, schools and community facilities. Finally, the winter temperatures in Scotland and North England are usually higher than in other regions of the UK, thus causing higher heating bills which would impact such households stronger by a CO_2 tax. Therefore, the spatial analysis of distributional impacts clearly indicates the areas to which the UK government should pay attention.

6.4 Conclusion and policy implications

This paper indicates that both a multi-GHG tax and a CO_2 tax are regressive, i.e. lower income groups would have to pay a higher share of their income on the tax unless additional redistributional measures are taken. However, the GHG tax would be distributed more equally across groups than the CO_2 tax. This is due to the fact that low income households spend a larger share of their income (12 percent) on food than high income groups (4 percent). Differences are even more pronounced for other essential consumption categories related to housing where the share of total income would be about 43 percent for low income households compared to only about 8 percent for high income households. Thus a shift from a CO_2 tax to a multi GHG tax with a reduction of tax payment on housing would more than compensate for the increase of tax payment for food in the case of low income households.

Notwithstanding the environmental benefits of shifting taxes towards a resource-base approach, social barriers represent a big issue for the government; it is a widely shared view among economists and policy analysts that one big obstacle of a carbon tax is represented by the tax being a regressive one (Ekins, 1999; Herber and Raga, 1995)). Alternative ways of designing and implementing the tax have to be considered on the basis of evidence showing how they can improve performance in terms of social-economic impacts without jeopardising the rationale for the tax (i.e. focus on the environmental goal).

Government might need to make sure that sufficient compensation is given to low income households in order to reduce their tax burden and secure social acceptability. (This assumes that a fairer income distribution is indeed a government policy. There are other regressive taxes, most notably VAT). The compensation can be introduced by either giving special emission allowance which would defeat the purpose of a carbon tax or through reducing other types of taxation or creating other transfer payments specifically for lower income groups (Wier et al., 2005)). A number of examples exist, for example in the Netherlands, where progressivity has been built into a 'green tax system' such as exemption for income tax for lower income brackets (European Environmental Agency, 1999; Vermeend and Van der Vaart, 1998)). In terms of sectoral effects of a carbon tax I found that electricity production would be the most affected sector. In order to reduce the carbon intensity of electricity production, the government might subsidize renewable energy production through technologies such as wind farms and solar power or encourage such production through feed-in tariffs (Mitchell et al., 2006)).

The situation is a bit more complicated with regards to GHG and food. Most of the GHG emissions are associated with methane emissions for meat production especially cattle and only a limited amount of technological options are available (especially with regards to the digestion system of cattle which can only partly be influenced through changes in feeding practices). In general, an increase in CO2 efficiency in agriculture is fairly limited. Moreover, food consumption is a sensitive issue as it represents a large consumption item for lower income groups; besides, meat consumption can only be replaced by switching to a more vegetarian diet and this opens the door to cultural issues or questioning habits.

An extra dimension is added when analysing the burden with regards to people's lifestyles and associated lock-in effects. For example, households grouped as Rural Isolation pay much higher carbon tax than the Suburban Comfort and Urban Intelligence households due to their relatively high demand for heating, electricity and transport as a result of their rural location. This is due to the relative sparse public transport infrastructure in remote locations and thus higher reliance on cars. Thus people who live in the country-side might be "locked" into their transport emissions to some extent. Also, the houses in rural area are usually larger and more exposed requiring more electricity and heating. Poor people might be locked into their emission patterns from housing, because they do not own the dwelling, which might be in poor condition and they might not have the means to finance retrofit measures easily. As electricity, heating, and transport are part of basic needs, the social barriers represent a big issue for the government. To tackle these issues the government may want to subsidize household energy conservation activities as well as the use of energy efficient products in order to motivate environmentally friendlier lifestyles and at the same time reduce both the tax burden and living costs.

It is important that all areas of government policy and investment are incentivizing a low carbon society. For example, infrastructure development has a strong role to play in shaping our consumption patterns. Our ability to access low carbon modes of transport is a good example. The need for spatial planning to deliver the infrastructure that allows and increases low carbon mobility solutions must go hand in hand with a carbon tax and/or trading scheme.

Finally, it is politically difficult to introduce a tax that would increase the problem of 'fuel poverty' that the UK Government sees as a very important issue. The use of a carbon tax in isolation from other policy measures would cause many of the problems highlighted above. For example, retrofitting houses has been identified as a key policy that will contribute over 50% of the 80% reduction required for the housing sector (Barrett and Dawkins, 2008). Therefore, the income generated from a carbon tax could be used to fund large-scale retrofitting of houses, starting with households most affected by the tax.

Chapter 7 : Research Summary and Future Outlook

Studies in this thesis emphasise the link of environmental input-output analysis to space. In this chapter, I firstly summarise the findings and policy implications with regards to the policy context for each case study. I then discuss the limitations of the study in conjunction with a suggestion of the future research plan.

7.1 Summary of case studies

Economic growth, economic structure change, urbanisation and growth of consumption have caused numerous environmental problems locally, nationally and globally. The increase of socio-economic activities in one region could have a serious impact on the environment in other regions. Spatial analysis of environmental issues with detailed sectoral level data information could be very useful with regards to environmental policy implications and help with sustainable natural resources management. In this section, I will summary the key findings from each case study.

Consumption and production water footprints for the UK

The Water Footprint, which is a measure for water consumption along the whole supply chain, has become an important indicator to address the use of water resources. This is particularly relevant for countries like the UK, which increasingly rely on products produced elsewhere in the world and thus impose pressures on foreign water resources. In Chapter 3, I found that 85 percent of the UK production water footprint is for its domestic final consumption, and the average consumption water footprint of the UK is more threefold of its production water footprints. About half of the UK consumption water footprints are associated with imports from Non-OECD countries (many of which are water scarce). In addition, I found that the water footprint differs considerably across sub-national geographies in the UK for both internal and external water footprints. This is mainly due to differences in the average income level across the UK. Some policy implications from this study have been discussed. Firstly, three quarters of the fresh water extraction caused by UK consumption took place in other world regions. It means that the UK is also responsible for the global water resource depletion. Therefore, the requirements of transferring advanced technologies from developed countries to developing countries should be discussed on the international forum in a more strategic way, in order to improve water efficiency for the virtual water exporting countries. Secondly, UK domestic final consumption also puts huge pressure on its domestic water resources, and there is a strong link between water footprints and per capita income. The results implied that increase of the water price for both domestic use and industrial use in the South-East and Greater London areas could reduce the internal water footprints and particularly help to reduce the water stress in the South-East and Greater London areas. Thirdly, the national and local governments should seriously take water scarcity into account when evaluating any policy to shift towards renewable energy sources, particularly biofuels.

Virtual water flows and water footprints in the Yellow River Basin, China

The three reaches in the YRB have very different characteristics in terms of water resources, economic development and household consumption. A site-specific MRIO was developed and applied in Chapter 4 to assess the regional virtual water flows and water footprint in the three reaches and the rest of China. It has been found that the production and consumption activities outside of the basin also increased stresses on the water resources in the YRB. It implied that the lower reach (the most water-scarce area of the basin) should reduce the export of water intensive and low value added agricultural products and use the blue water for the products with high value added. The upper reach (water-rich but lower water productivities area) can greatly benefit from importing advanced irrigation system from the lower reach and other East-Coastal regions in China. Effective water pricing policy in water scarce regions, especially the lower reach, may stimulate importing water intensive goods and reduce the burden on local water resources. Moreover, the water footprint of urban households is more than double of the rural households across the whole basin. Effective water pricing policy or labelling water intensive goods may help to direct households towards lower water intensive lifestyles, and it is particularly important for urban households who generally have much larger water footprint.

Regional driving forces of China's CO_2 emissions

The significant regional disparity, in terms of physical geography, local economy, demographics, industrial structure and household consumption, leads to large discrepancies of regional CO_2 emissions in China. Identifying the main drivers for the growth of regional CO_2 emissions may help to reduce China's overall CO_2 emissions through designing specific and appropriate mitigation options for the respective region. In Chapter 5, I carried out a regional SDA study on China's CO_2 emissions 2002 – 2007. The results show that changes in final consumption were the most important driving force for the growth of CO_2 emissions in most regions in China due to changes in lifestyles. In urban areas, people have more energy intensive lifestyles. Thus, a reduction of household consumption of energy intensive goods and services may decrease both direct and indirect CO_2 emissions through introducing green labels. I also observed that there is a large gap between the three economic zones in terms of improvements in emissions intensity due to the fact that the Eastern-Coastal economic zone possesses more advanced production technologies compared with the other two economic zones. Technology transfer from the Eastern-Coastal regions to the Central and Western regions may eventually drive down the emissions through improving the energy efficiency and reducing the CO_2 emissions intensity, although it has shown that in the past, newly developing regions do not necessarily employ the best technologies available in the more developed coastal regions. Export is also one of the important driving forces for fast emissions growth in China. Central and Western regions export emissions intensive goods to the East-Coastal regions, and the East-Coastal regions further process the goods and either export them back to other Chinese regions or sell to the international markets. Therefore, it is necessary to increase technology investment in the Central and Western regions through regional coordination and inter-region policies. In addition, the fast growth of the economy requires a large scale of infrastructure investment, which at the same time causes a huge amount of emissions. For a long term energy savings and emissions reduction strategy, investment should be focused on energy efficient buildings and other industries.

Distributional effects of a potential climate change taxation in the UK

Carbon taxation is a frequently suggested economic instrument to help to mitigate GHG emissions. Policy makers often hesitate to use such an instrument due to its disproportional effects on the poor. In Chapter 6, I specifically looked at distributional effects on different income groups and lifestyle groups by comparing CO_2 and GHG taxes through combining economic input-output model with geo-demographic marketing database (MOSAIC). In this study, I found that a multi-GHG tax is more efficient than a CO_2 tax alone, due to lower marginal abatement costs, and that both taxes are regressive, with lower income households paying a relatively larger share of their income for the taxes than higher income households. The poorest households could pay three times more as a proportion of their income towards a CO_2 tax than higher earners versus two times for a GHG tax. The results have also shown that there is inequality of a CO_2 or GHG tax burden across lifestyle groups. *Rural Isolation* households pay a higher share of their income for a CO_2 and GHG tax than *Suburban Comfort* households and *Urban Intelligence* households mainly due to higher tax burden on housing and transport. When shifting from a CO_2 tax to a multi-GHG tax the tax burden for housing and transport decreases leading to a more equal distribution of the tax burden across lifestyle groups, but at the same time there is a slight increase of tax payment on food items. A CO2 tax puts a higher burden on fuel whereas a multi-GHG tax affects food items more. A spatial analysis across 434 UK local authorities has shown that households in North England and Scotland would be affected most by a CO_2 tax due to a higher proportion of rural households and lower temperatures in the winter. The housing-related carbon emissions are the largest component of the CO_2 tax payments for low income groups, and arguments could be made for compensation of income losses to reduce 'fuel poverty' through further government intervention.

7.2 Limitations and future research plans

Each of the case study chapters of this thesis (i.e. Chapters 3-6) has its own sets of limitations, in terms of methodological shortcomings and data availability and quality. In this section, I discuss the limitations of each respective chapter and suggest improvements that can be made regarding future research.

In Chapters 3 and 4, the lack of detailed agricultural sectors in the IO tables and associated water consumption were the main drawbacks of these two studies. Agriculture is the largest water consuming sector, and a detailed analysis of different crops on water use can provide more rigorous results in terms of agriculture production activities, regional trade of agricultural products and associated virtual water flows. In Chapter 3, there is no detailed sectoral level industry water consumption data available for the all EU-OECD countries, Non-EU-OECD countries and Non-OECD countries and I had to assume that the countries in the same group have the same water coefficients for the industrial sectors. For example, I use direct water coefficients of Australia for Non-OECD countries. Many national governments have already started to include natural resource extraction and environmental pollution into their national accounts, and this provides high quality of environmental data for use in research, including water resources and water consumption. Therefore, the results should be updated when better water data become available. As described in Chapter 3, I grouped countries into four world regions (UK, EU-OECD countries, Non-EU-OECD countries and Non-OECD countries). Therefore, the spatial relationships are shown at very aggregate level only. A further research on assessing water footprint and global virtual water flow based on a more detailed MRIO model is highly recommended. For instance, a 113-region MRIO model based on GTAP database has been introduced recently (GTAP, 2003). A full 113 regions MRIO model can be used and the results at country level can be calculated. In Chapter 4, a limitation, apart from highly aggregated agricultural sector, is that the MRIO table for the YRB was built by using regional rail transportation data. This is because the regional rail transportation data is the only data currently available to estimate the regional trade flows from the public data sources. The quality of the MRIO table would be much improved if more data were available, such as the prices of detailed commodities at regional level, through applying the gravity models suggested by Miller and Blair (2009) to estimate inter-regional trade flows.

In Chapter 5, I used a single regional IO model, but not a comprehensive MRIO model, for each of the SDA studies for 28 regions in China. However, the single region IO models cannot capture how a factor in one region impact on the emissions in other regions. This is because there is no MRIO table available for the study years in China. A MRIO SDA study would be able to show how drivers behind one region's consumer emission changes relate to changes in producer emissions across all regions in China. So far, no MRIO SDA study has been carried out for China for the years 2002-2007, and thus, a development of MRIO SDA on China's CO_2 emissions will be of high-value to the SDA study on China's environmental research and discussions on policy implications.

In Chapter 6, four limitations of this study should be noted. Firstly, I do not consider how a tax would work in tandem with the existing EU-Environmental Trading Scheme[8]. While such a co-existence would make the assessment of the distributional impacts and the design of an appropriate policy response more complex, I would expect a carbon trading system – on a general level – to have similar regressive effects than a tax (Dinan and Rogers, 2002). Thus, most of the discussion would apply to both policies. Secondly, this study assumes that price changes are entirely related to the direct and indirect GHG emissions associated with a particular consumption item. Differences in prices caused, for example, by different pricing strategies a company might apply when passing on the carbon taxes to the consumers are not included. Thirdly, this study does not model the behavioural response of consumers to higher prices and the associated changes in production as well as their price effects. Instead I assume that the purchasing power remains unaffected by the tax and there is no change in economic structure and

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[8] In 2003, the European Council formally adopted the Emissions Trading Directive (Directive 2003/87/EC). The Directive laid out the framework for the European Emissions Trading Scheme (the 'EU ETS'). The scheme started in 2005. From this date emissions from the companies covered by the scheme (currently only the power sector and energy-intensive industrial sectors) were capped across 25 European countries.

consumption patterns. I therefore only consider the effect of consumers having to pay higher prices for their goods and services in the short-term. Finally, another shortcoming is that the abatement activities may affect wages, returns to capital and labour supply (As mentioned by Fullerton, 2009), which cannot be measured by our model. However, even though some of the assumptions I make might appear strong, I believe that they provide helpful simplifications in the context of the analysis presented. Clearly, assessments focusing on the long-run effects of a carbon tax would need to model at least some of the factors outlined in this section explicitly.

From above four case studies, I conclude that linking environmental input-output models to space can present the spatial relationships of different regions in terms of environmental issues and build up consumption based spatio-environmental inventory. The results from the environmental input-output models with a spatial dimension provide useful information for sustainable environmental strategies at different spatial scales, and enhance a better understanding of the spatial inter-dependency of consumption and production activities and associated environmental issues. However, the spatial resolutions for the production activities are still very aggregate, where a country or region is considered as a spatial unit. Thus, the detailed geographical locations of production activities and associated environmental problems should be captured and linked to the spatio-consumption inventories through the environmental input-output framework. Two research areas are planned for the future. One research study is to link environmental input-output model to both geo-demographic consumption database and the local toxics release inventory and couple with air pollution dispersion model. It will allow assessing how the household consumption in one place may cause spatial impacts of air pollution in other areas. This study will be of particular interest to those who focus on the consumption activities and associated health problems. Another research study is to carry out a spatial analysis of land use and land cover changes through strong bio-physical linkage of input-output model and assess the net carbon flux of consuming goods and services from both fossil fuels combustion and land use changes. It is of particular interest to those who devise the current climate change mitigation strategies, as in the past, climate change studies were either focusing on calculating embedded carbon in goods and services from fossil fuel or measuring the changes of carbon inventories due to land cover and land use changes.

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Appendix One

Consumption water footprint by degree of Urbanization (m^3/capita/year)

			Min	Max	Average	SD
1	Major Urban	Districts with either 100,000 people or 50 percent of their population in an urban area of more than 750,000	906	1,988	1,149	194
2	Large Urban	Districts with either 50,000 people or 50 percent of their population in one of the 17 urban areas of the UK with a population between 250,000 and 750,000	916	1,277	1,080	84
3	Other Urban	Districts with fewer than 37,000 people and more than 26 percent of their population in rural settlements and large market towns	952	1,313	1,066	78
4	Significant Rural	Districts with more than 37,000 people and more than 26 percents of their population in rural settlements and market towns.	988	1,304	1,143	83
5	Rural-50	District with at least 50 percent but less than 80 percent of their population in rural settlements and larger market towns	909	1,329	1,135	84
6	Rural-80	Districts with at least 80 percent of their population in rural settlements and larger market towns	982	1,262	1,146	59

Appendix Two

MOSAIC Database

MOSAIC is a commercial geo-demographic market segmentation system, which classifies all consumers in the UK according to 11 neighborhood groups and 61 neighborhood types, which can be interpreted as lifestyles. The MOSAIC lifestyle profiles are mainly based on census data which is augmented with a variety of other data sources including expenditure and income information, electoral roll, Experian lifestyle survey information, and consumer credit activities, alongside the post office address file, shareholders register, house prices and council tax information, and ONS local area statistics (see (Experian, 2008)).

Description of MOSAIC groups

Group	Group Description	% Household	Type	Type Description	% Househol
A	Symbols of Success: *Symbols of Success* contains people whose lives are 'successful' by whatever yardsticks society commonly uses to measure success. These are people who have rewarding careers rather than jobs, who live in sought after locations, who drive the more modern and expensive cars and who indulge in the most exotic leisure pursuits. Most, though not all, appear to enjoy stable household arrangements.	9.62	A01	Global Connections	0.72
			A02	Cultural leadership	0.92
			A03	Corporate Chieftains	1.12
			A04	Golden Empty Nesters	1.33
			A05	Provincial Privilege	1.66
			A06	High Technologists	1.82
			A07	Semi-Rural Seclusion	2.04
B	Happy Families: *Happy Families* contains people whose focus is on career, home and family. These are mostly younger age groups who are	10.76	B08	Just Moving in	0.91
			B09	Fledgling Nurseries	1.18
			B10	Upscale New Owners	1.35

	married, or at least in a permanent relationship, and are now raising children in post war family houses, often in areas of the country with rapidly growing populations. The focus of expenditure is on equipment for the home and garden, and the immediate family unit is the principal focus of leisure activities.		B11 B12 B13 B14	Families Making Good Middle Rung Families Burdened Optimists In Military Quarters	2.32 2.86 1.96 0.17
C	Suburban Comfort: *Suburban Comfort* comprises people who have successfully established themselves and their families in comfortable homes in mature suburbs. Children are becoming more independent, work is becoming less of a challenge and interest payments on homes and other loans are becoming less burdensome. With more time and money on their hands, people can relax and focus on activities that they find intrinsically rewarding.	15.10	C15 C16 C17 C18 C19 C20	Close to Retirement Conservative Values Small Time Business Sprawling Subtopia Original Suburbs Asian Enterprise	2.81 2.84 2.93 3.08 2.41 1.02
D	Ties of Community: *Ties of Community* is comprised of people whose lives are mostly played out within the confines of close knit communities. Living mostly in older houses in inner city neighbourhoods or in small industrial towns, most of these people own their homes, drive their -	16.04	D21 D22 D23 D24 D25 D26 D27	Respectable Rows Affluent Blue Collar Industrial Grit Coronation Street Town Centre Refuge South Asian Industry	2.65 3.12 3.82 2.81 1.13 0.88 1.62

	own cars and hold down responsible jobs. Community norms rather than individual material ambitions shape the pattern of most residents' consumption.			Settled Minorities	
E	Urban Intelligence: *Urban Intelligence* mostly contains young and well educated people who are open to new ideas and influences. Young and single, and few encumbered with children, these people tend to be avid explorers of new ideas and fashions, cosmopolitan in their tastes and liberal in their social attitudes. Whilst eager consumers of the media and with a sophisticated understanding of brand values, they like to be treated as individuals, and value authenticity over veneer.	7.19	E28 E29 E30 E31 E32 E33 E34	Counter Cultural Mix City Adventurers New Urban Colonists Caring Professionals Dinky Developments Town Gown Transition University Challenge	1.36 1.27 1.36 1.08 1.10 0.76 0.26
F	Welfare Borderline: *Welfare Borderline* is comprised of many people who are struggling to achieve the material and personal rewards that are assumed to be open to all in an affluent society. Few hold down rewarding or well-paying jobs and, as a result, most rely on the council for their accommodation, on public transport to get around andon state benefits to	6.43	F35 F36 F37 F38 F39 F40	Bedsit Beneficiaries Metro Multiculture Upper Floor Families Tower Block Living Dignified Dependency Sharing a Staircase	0.71 1.67 1.72 0.49 1.34 0.50

	fund even the bare essentials. The lack of stability in many family formations undermines social networks and leads to high levels of anti-social behaviour among local children.				
G	Municipal Dependency: *Municipal Dependency* mostly contains families on lower incomes who live on large municipal council estates where few of the tenants have exercised their right to buy. Often isolated in the outer suburbs of large provincial cities, Municipal Dependency is characterised as much by low aspirations as by low incomes. Here people watch a lot of television and buy trusted mainstream brands from shops that focus on price rather than range or service.	6.71	G41 G42 G43	Families on Benefits Low Horizons Ex-industrial Legacy	1.21 2.64 2.86
H	Blue Collar Enterprise: *Blue Collar Enterprise* comprises people who, though not necessarily very well educated, are practical and enterprising in their orientation. Many of these people live in what were once council estates but where tenants have exercised their right to buy. They own their cars, provide a reliable source of labour to local employers and are streetwise	11.01	H44 H45 H46 G47	Rustbelt Resilience Older Right to Buy White Van Culture New Town Materialism	3.00 2.67 3.17 2.17

	consumers. Tastes are mass market rather than individualistic and focus on providing comfort and value to family members.				
I	Twilight Subsistence: *Twilight Subsistence* consists of elderly people who are mostly reliant on state benefits, and live in housing designed by local authorities and housing associations. Some live in old people's homes or sheltered accommodation, while others live in small bungalows, set in small enclaves within larger council estates. Most of these people spend money only on the basic necessities of life.	3.88	I48 I49 I50	Old People in Flats Low Income Elderly Cared for Pensioners	0.83 1.63 1.43
J	Grey Perspectives: *Grey Perspectives* consists mostly of pensioners who own their homes and who have some source of income beyond the basic state pension. Many of these people have, on retirement, moved to the seaside or the countryside to live among people similar to themselves. Today many of these people have quite active lifestyles and are considered in their purchasing decisions.	7.88	J51 J52 J53 J54 J55 J56	Sepia Memories Childfree Serenity High Spending Elders Bungalow Retirement Small Town Seniors Tourist Attendants	0.75 1.34 1.53 1.26 2.71 0.30
K	Rural Isolation: *Rural Isolation* contains	5.39	K57 K58	Summer Playgrounds	0.29 1.74

	people whose pattern of living is distinctively rural. They live not just outside major population centres but also deep in the countryside, in small communities which have been little influenced by the influx of urban commuters. These are places where people with different levels of income share attachments to local communities, and where engagement with the community and with the natural environment are more important to most residents than material consumption.		K59 K60 K61	Greenbelt Guardians Parochial Villagers Pastoral Symphony Upland Hill Farmers	1.64 1.31 0.41