Full Biophysical and Socio-economic Carbon Accounting for the UK

Kuishuang Feng[1*], Klaus Hubacek[1], Yim Ling Siu[1], Mette Termansen[1], Mike Kirkby[2], Brian Irvine[2]

[1]Sustainability Research Institute (SRI), School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

[2] School of Geography, University of Leeds, Leeds, LS2 9JT, UK

* Corresponding author

Phone: +44 1133436366. Fax: +44 113 3436716. Email: lec3kf@leeds.ac.uk

ABASTRCT

This research proposes a framework for a carbon accounting system and analytical model for the UK that 1) accounts for embodied carbon in products and services of the UK economy able to distinguish between 120 economic product groups and services and their respective life-cycles; 2) accounts for effects of socio-economic changes on land use and land cover through integrated bio-physical and socio-economic models; and 3) models carbon fluxes in different land use and land cover categories, including vegetation, soil and hydrological dynamics; 4) serves as a basis for policy evaluation and modeling future change through scenarios. In this research, we develop an integrated accounting and analytical framework based on input-output (IO) model by extending a land use model and a bio-physical model accounting for carbon fluxes in different types of soils. The proposed framework will be used to model carbon fluxes between social, economic and ecological systems. In order to combine economic and ecological data within a consistent methodological framework, the extended IO tables include a set of natural resource parameters that represent the flow of environmental resources to each economic sector, and flows from the economy to the environment and interactions within the ecosystem. The key links of the natural and human systems identified are land use and land use changes regarding to the carbon flux. For example, changes in land use and management in agricultural and forestry critically affect atmospheric Green House Gas (GHG) concentrations, in addition to emissions from social and economic systems. A set of scenarios which represent changes in lifestyles, consumer choices or technical change will also be developed and used to evaluate the ripple effects through an economic system and its implications for ecosystems and carbon cycles.

Keywords: Carbon emissions, Carbon accounting, input-output model, Land-use change, Carbon flux.

1.0 INTRODUCTION

It is nowadays broadly accepted that there is an urgent need to control atmospheric greenhouse gas (GHG) concentrations to prevent dangerous interference with the climate system. Among greenhouse gases, CO2 has received the most attention because of its concentration in the atmosphere and because it is the main gas emitted by burning fossil fuels (Cacho et al. 2003). Although the main emphasis in the global climate change debate has concentrated on reduction of CO2 emissions from fossil fuels, people have recognized the potential contributions of carbon sequestration by transferring carbon from the atmosphere to the terrestrial biosphere to mitigate climate change (Cacho et al. 2003; West and Marland 2002). The UK, as one of the main industrialized countries, is considered to be seriously impacted by climate change, and also plays a significant role for the reduction of CO2 concentration in the atmosphere to achieve the Kyoto Protocol (KP) agreement and its domestic targets. In the UK climate change is predicted to result in an increase in mean annual temperature of between 2.5and 3 °C by the end of the century (DoH 2008). Greater warming is more likely to occur in the south and east of the UK. The UK's summer will become hotter and drier with average summer temperatures rising between 0.5 and 2 °C. Extreme weather events such as very hot summer days (e.g. similar to august 2003 and July 2006 which were 3 °C above average) are seems to become a general occasion. In contrast, the number of cold winter days will decrease while winter rainfall, winter storms and windy weather is projected to happen more frequently. Depending on the region, the sea level around the UK coast is estimated to increase by 80 cm. Extreme sea levels and storm surge events may become more frequent in some coastal locations (UKCIP 2007).

It has already been recognised the necessity of developing a system of national accounts that provides information about the actual relation between the economy and the environment in order to give a rigorous way to approach the reduction of carbon emissions and suggest feasible solutions (Hellsten et al. 1999). With the purpose of integrating international environmental accounts, the United Nations (1993) with some other international organisms developed an motivated system known as *System of Integrated Environmental and Economic Accounts* (SEEA). The National

Accounting Matrix including Environmental Accounts (NAMEA) is a further step developed in Netherland (De Boo et al. 1991; De Haan et al. 1993).

The input-output model is a very useful framework for environmental accounting and analysis because (1) its level of sectoral detail allows the analyst to take account of the fact that different activities produce different types and levels of pollution, and (2) its representation of sectoral interdependencies makes it possible to project both the direct and indirect environmental impacts of various activities (Xu et al. 1994).

1.1 Aims and Objectives

In this research, we aims to develop a conceptual framework of a carbon accounting system model based on the UK. This framework will be used to 1) account for embodied carbon in products and services of the UK economy distinguishing between 120 economic product groups and services and their respective life-cycles; 2) account for effects of socio-economic changes on land use and land cover through integrated bio-physical and socio-economic models; and 3) model carbon fluxes in different land use and land cover categories, including vegetation, soil and hydrological dynamics; 4) serve as a basis for policy evaluation and modeling future change through scenarios. The proposed framework will be used to model carbon fluxes between social, economic and ecological systems. In order to link economic and ecological models within a consistent methodological framework, the extended IO tables include a set of natural resource parameters that represent the flow of environmental resources to each economic sector, and flows from the economy to the environment and interactions within the ecosystem. The key links of the natural and human systems with regards to the carbon fluxes are land use and land use changes. For example, changes in land use and management in agricultural and forestry critically affect atmospheric Green House Gas (GHG) concentrations, in addition to emissions from social and economic systems.

1.2 Research Outline

In this research, we firstly review the literatures on applications of conventional Input-Output approach and extended environmental Input-Output approach in section 2. In section 3, we represent the carbon accounting conceptual framework, and state the further detail of conceptual framework including methodology, model components, model equations and the integrated model for net carbon fluxes. And then, we set up six scenarios for net carbon fluxes in the UK, in terms of the changes of population, lifestyle and technology in section 4. Finally, we illustrate the proposed future research plans including applications of integrated model, data collection, and awareness of the current limitations, and conclude the potential benefit of this research.

2.0 LITERATURE REVIEW

In this research, the conceptual carbon accounting system is based on input-output model with a large number of interacting elements, such as industrials, emissions and land-uses. In this section, we provide selective literature review on input-output analysis and its extensions.

2.1 Leontief's Basic Input-Output Model

Input-output modelling is a quantitative approach to analyse the interdependences within an economic system, which was firstly presented by Wassily Leontief in the late 1930s. The fundamental rationale of the input-output (United Nations et al.) model is to analyse the interdependence of economic sectors in monetary units in an economy (Miller and Blair 1985). It was initially applied to determination of direct and indirect input requirements for U.S. industrial sectors. After the World War II, the input-output techniques have been vitally improved while the approach was extended to many fields such as energy, materials flows and environmental pollution and applied in many other countries, regional or even company level. And many multi-regional input-output models have been built in recent years.

An input-output model demonstrates a detailed flow of goods and services between producers and consumers. The core perspective of input-output approach is that the technology of production of goods and services are determined by final demand generated by users of those products (Duchin and Lange 1994). Therefore, the structure of an economy would be coordinated or changed in terms of the changes of people's consumption patterns and lifestyles.

2.2 Environmental Input-Output Analysis

Input-output models have been extended by many researchers to incorporate links to environmental pollution generations and abatement associated with interindustry activity since the late of 1960s. Cumberland (1966) was one of the earliest researcher to apply the input-output analysis for environmental issues. The approach in Cumberland's research was to add new rows and columns to an input-output in order to identity environmental benefits and costs due to economic development. His model used monetary values on environmental effects rather than measuring the emission in physical terms. However, the environmental impacts are very difficult to be estimated in monetary terms. Moreover, Cumberland's model does not incorporate the flows between the environment and the economy (Richardson 1972). His model is much closer to a Cost-Benefit analysis of environmental effects rather than an analysis of studying the interactions between the economy and the environment (Richardson 1972).

Leontief (1970) proposed a approach to simply augment the technical coefficient matrix with a set of pollution generation and / or abatement coefficients. In the case of pollution generation, coefficients reflect the amount of a particular pollutant generated per dollar's worth of industry output. In the same theory, the pollution abatement coefficients reflect inputs to pollution-elimination activities. With this model he was able to predict the direct cost of abatement, the amount of pollution abated and the indirect impact on gross output (Guan and Hubacek In Press; Rose and Miernyk 1989). Many studies have been based on this framework for investigating environmental emissions or resource consumption triggered by economic development or trade in both single country and multi-regional approaches. The extended input-output model was applied to analyse air pollution by many studies (e.g. Giarratani 1974; Forsund 1985; Tamura and Ishida 1985). Also, the extended input-output model broadly applied to carry out the studies on water consumption and pollution (e.g. Carter and Ireri 1970; Xie et al. 1991; Xu et al. 1994; Guan and Hubacek 2006; Bockarjova 2007; Guan and Hubacek In Press; Okadera et al. 2005; Hubacek and Sun 2005; Lenzen and Foran 2001; Duarte et al. 2002; Leistritz et al. 2002; Lange 1997, 1998; Lange et al. 2007). Some researches used environmental input-output model to analyse the changes of land-use (Fischer and Sun 2001; Hubacek and Sun 2001).

Physical Input-output Tables (PIOT) have been discussed for a long time. (e.g. Georgescu-Roegen 1979; Strassert 2001) and have been empirically used in biology studies (e.g. Hannon and Ruth 1997). The physical input-output tables record all the flows and transactions of goods and services in physical units (Dietzenbacher 2005). PIOT is a powerful toos in current input-output analysis with regards to material flow accounting, energy accounting, and land-use. The most recent analysis of PIOTs are including Hubacek and Giljum (2003), Suh (2004). However, the major disadvantage is that no standardized methodology had yet been agreed upon according to the PIOTs compiled so far. The existing PIOTs are much different, In terms of the number of sectors reported including the disaggregation into product groups and the inclusion or exclusion of specific materials (Hubacek and Giljum 2003).

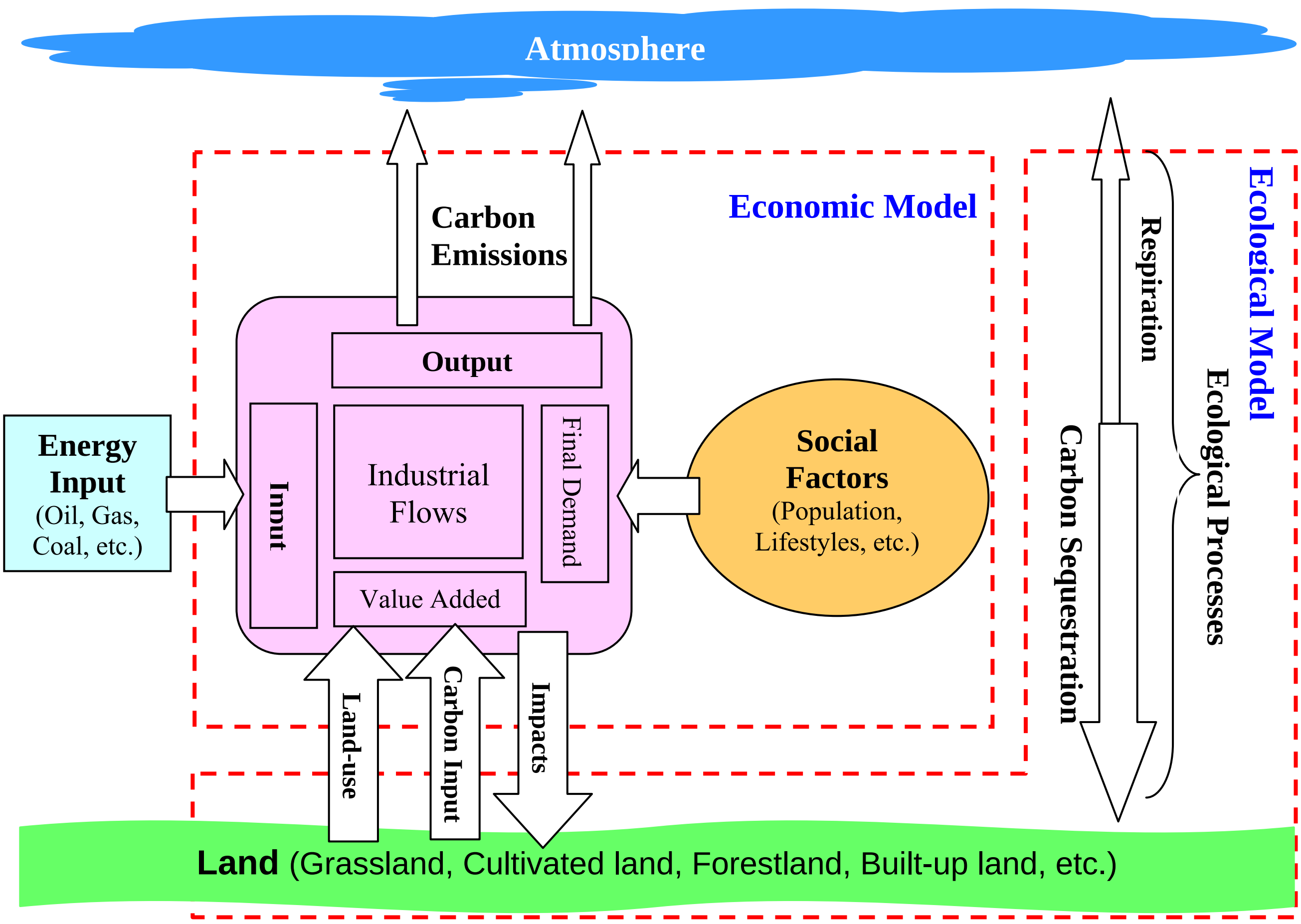
Input-output model is also a popular tool to the studies of carbon emission and carbon accounting in many regions and countries. Some of studies were focused on carbon emission from industry groups (e.g. Hetherington 1996; Casler and Rose 1998), and some of them measured the embodied carbon in regional, national or international trading (Liang et al. 2007; McGregor et al. 2007; Peters and Hertwich 2006; Machado et al. 2001), as well as measuring progress of carbon reduction (Druckman et al. 2008). From above illustration we can know that all studies of carbon emission and carbon accounting concentrated on carbon content of industrial goods and services, and discussed to reduce carbon emissions from social and economic activities. However, the land being used for social-economic purposes also has a large potential to sequester the carbon from atmosphere, so that reduce carbon concentration in atmosphere. Therefore, it is necessary to develop a full biophysical and socio-economic carbon accounting framework for current analysis and future projection of net carbon fluxes. This framework is based on integrated ecological and economic approach through applications of extended input-output models.

There are some disadvantages to use input-output models as projections and forecasting tools. As the period of projection becomes longer, the accuracy tends to decrease, because our ability to forecast the new final demands accurately will diminish and also the coefficient matrix may be likely to get out of date (Miller and Blair, 1987). There are a number of reasons for this inaccuracy (Miller and Blair): Firstly, the technology changes over time; some new techniques may applied in certain sectors. These changes will be accelerated by the rapid economic growth globally. Secondly, prices change and vary over time which may result in replacement of the inputs during production. For example, solar energy may replace oil and natural gas as an energy source due to its relative cheaper price in future. Finally, new products are invented which indicates there will be a new sector, row and column, the coefficient table will change.

3.0 THE CARBON ACCOUNTING CONCEPTUAL FRAMEWORK

The core of this carbon accounting conceptual framework is to integrated ecological model with economic input-output model. In order to set up the integrated carbon accounting framework, it is important to understand the carbon flow between socio-economy and physical environment.

Figure 1: Conceptual Framework of Carbon Accounting



Carbon emissions can be considered as the output of economy to natural environment during the economic processes, which is mainly accumulated in the atmosphere. At the same time, a part of carbon is also sequestered from atmosphere by different types of land, which being used to satisfy the socio-economic activities. Hence, carbon accounting framework should include both emissions and sequestrations. In this accounting framework, land is the key link between ecological model and economic model, as it also considered as primary input of economy. The changes of socio-economic activities can directly and indirectly impact the land use, at the same time influence the carbon sequestration in terms of land-use changes. The following sections state the model components and model equations will be applied for this carbon accounting framework.

3.1 Methodology

Based on carbon accounting conceptual framework, a set of extended input-output models including carbon emission models and land-use are integrated with carbon sequestration model to measure the net carbon flux in the UK. In order to interpret the full carbon accounting system clearly, we describe each model in detail in the following sections.

3.1.1 Economic Input-Output Model

Input-output analysis is an approach of systematically quantifying the interrelationships between the various sectors of a complex economic system based on the technological notion. The starting point of the model is a set of input-output accounts which summarizes all the flow of goods and services that occur within an economy. These accounts include sales sectors and purchases sectors. The output of each sale sector is made up of two aggregate components: intermediate demand, which is the sale of goods and services from one production sector to another and final demand, which is the sales of goods and services for a 'final' purpose such as consumption, investment, export, or sales to the public sector. Correspondingly, the purchase of each sector can be broken down into two components: intermediate input, which includes payments to labour, capital (debt services and profits), and taxes. A simplified input-output table for an economy is show in Table 1. In terms of the value of sales and purchases balance for all sectors, the sum of all elements in a row (output) is equivalent to the sum of all elements in the corresponding column (input).

Table 1: Simplified Input-Output Accounts

		Processing sectors (Purchases)	Final demand				Total Output
		1 … j … n					
Processing sectors (sales)	1 … i … n	**Z**	h_i	g_i	i_i	e_i	x_i
Payments sector	wages	w_j					W
	Capital	k_j					K
	Taxes	t_j					T
Total outlays		x_j	H	G	I	E	X

The basic linear equation of output accounts can be summarized as:

$$x_i = \sum_{j=1}^{j=n} z_{ij} + y_i \qquad \text{Eq. (1)}$$

$$y_i = c_i + g_i + i_i + e_i \qquad \text{Eq. (2)}$$

where x_i is the total output of industry i, z_{ij} is the amount of output of industry i sold to industry j (intermediate demand), and y_i is the final demand for the output of industry i. Final demand consists of household purchases h_i, government purchases $g_{i,}$ investment i_i and net exports e_i (the difference between the export of the outputs of sector i and the imports of like goods). The basic purchase accounts can be summarized mathematically as:

$$x_j = \sum_{i=1}^{i=n} z_{ij} + v_j \qquad \text{Eq. (3)}$$

$$v_j = w_j + k_j + t_j \qquad \text{Eq. (4)}$$

where v_j is the payments of sector j to value added, which includes payments to labour w_j, payments to capital k_j and taxes t_j. W, K, and T are total labour income, capital income, and government revenue, respectively. The input-output model focuses on the output accounts, and assumes final demand to be exogenous. A further assumption of the input-output model is that the industry technology remains constant for a base period of time. Technical coefficient a_{ij} defined by dividing the inter-sectoral flows from i to j (x_{ij}) with total output of j (x_j),

$$a_{ij} = {x_{ij}} / {x_j} \qquad \text{Eq. (5)}$$

where a_{ij} is the value in pounds of sector i output used as input in producing one pound's worth of sector j output. Thus, Equation (1) can be rewritten so as to include the technical coefficient (a_{ij}), and the developed equation is:

$$x_i = \sum_{j=i}^{j=n} a_{ij} x_j + y_i \qquad \text{Eq. (6)}$$

The Equation (6) is defined as the purchases that sector j makes from sector i per total effective production unit of sector j, and represent the direct input required by sector j. In matrix notation and for the economy as a whole, the Eq (3) can be shown in matrix notion as:

$$X = AX + Y \qquad \text{Eq. (7)}$$

where A is the coefficient matrix.

To solve for x, we get total output flowed to final demand

$$X = (I - A)^{-1} Y \qquad \text{Eq. (8)}$$

where $(I\text{-}A)^{-1}$ is known as the Leontief inverse matrix, which shows the total production of each sector required to satisfy the final demand in the economy. Denoting its elements by the symbol α_{ij}, we can write the equation as follows:

$$x_i = \alpha_{i1} y_1 + \alpha_{i2} y_2 + \ldots + \alpha_{in} y_n \qquad \text{Eq. (9)}$$

or

$$x_i = \sum_{j=1}^{j=n} \alpha_{ij} y_j \qquad \text{Eq. (10)}$$

where α_{ij} is the increase in production generated by sector i if the demand of sector j increases in one unit. In other words, the coefficients are 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:

$$\Delta X = (I - A)^{-1} \Delta Y \qquad \text{Eq. (11)}$$

In general, the multipliers of the famous $(I\text{-}A)^{-1}$ Leontief inverse account for the total effect of the exogenous impact by change in final demand as discussed above.

3.1.2 Carbon Emission Model

CO2 accumulates in the atmosphere after the economic process. In order to measuring total direct and indirect carbon emission from economic activities, we develop the economic input-output table into carbon emission table adding a carbon emission column into the traditional input-output table. Then, we generate the total carbon emission multipliers by multiplying a diagonal direct carbon emission coefficients matrix *D* with the Leontief inverse $(I\text{-}A)^{-1}$. The direct carbon emission coefficients are the quantity of carbon emissions per unit monetary output for each industry sector *i*, and is calculated according to:

$$d = \frac{C_{pi}}{x_i} \quad \text{Eq.(12)}$$

where C_{pi} is the carbon emission from sector *i*. x_i is the output of sector *i*. Hence, the total carbon emissions throughout the consumption sectors show in Eq. (13).

$$C_p = D(I - A)^{-1}Y \quad \text{Eq. (13)}$$

3.1.3 Land-use Model

For application in land use, the typical I-O table is augmented by a representation of inputs and outputs of land. The land requirement coefficient vector (f_j) is defined as the ratio of total land use in each sector (L_j) over total sectoral output (x_j).

$$f_j = \frac{L_j}{x_j} \quad \text{Eq. (14)}$$

The land use coeffiecient vector (f_j) represents land use in hectares per one thousand pounds of output of sector *j*. This is equivalent to the inverse of sectoral land productivity (p_j) which represents the output in pound on one hectare of land:

$$p_j = \frac{x_j}{L_j} \quad \text{Eq. (15)}$$

In the short term, producers are able to extend their output without significantly expanding their land, particularly for industrial and service sector. Therefore, the link between output and land use is best perceived as a long-run relationship (Xu et al. 1994). In order for the final demand of a given sector to expand, the output of other sectors must expand in response to the input requirements of the given sector. Since all economic activities consume space, in the long-run, there must be increases or changes in land use or land productivity in order to achieve significant increases in output.

In order to link land-use changes in economic sectors to those in land categories (such as cultivated land, grassland, forestland, etc.), the vector representing the output (Eq. 8) is pre-multiplied by a diagonal land requirement coefficient matrix (F) and a land distribution matrix (*R*).

$$L = RF(I - A)^{-1}Y \qquad \text{Eq. (16)}$$

The land distribution matrix R gives the mapping relationship between land uses in economic sectors and the natural categories of land cover, and the attributes in R are the shares of the former in the latter (Hubacek and Sun 2001). The changes in land use *(ΔL)* triggered by the changes in output (*ΔX)* as given in Eq. (17).

$$\Delta L = RF\Delta X \qquad \text{Eq. (17)}$$

3.1.4 Carbon Sequestration

Annual Net Primary Productivity (NPP) (in g C m^{-2} year) is accumulated from the different between gross primary productivity (GPP) and autorespiration (Ra) on each day:

$$NPP = \sum_{i=1}^{365}(GPP - R_a) \qquad \text{Eq. (18)}$$

where NPP is the ability of carbon sequestration by different types of land (e.g. crops land, forest, and build-up land). Here, we use S to represent the NPP matrix in terms of land-use types. Therefore, the total carbon sequestration can be measured by multiplying NPP matrix with Land-use matrix, which is shown in Eq. (19).

$$C_s = SL \qquad \text{Eq. (19)}$$

where C_s indicates the total carbon sequestration. Through substituting for L in Eq. (19) using Eq. (16), we can obtain Eq. (20) as below:

$$C_s = SRF(I - A)^{-1} Y \qquad \text{Eq. (20)}$$

3.15 Net Carbon Flux Model

The net carbon flux is accumulated from the difference between total carbon emission from socio-economic activities and total carbon sequestration by the land being used for socio-economic activities which is shown in Eq. (21).

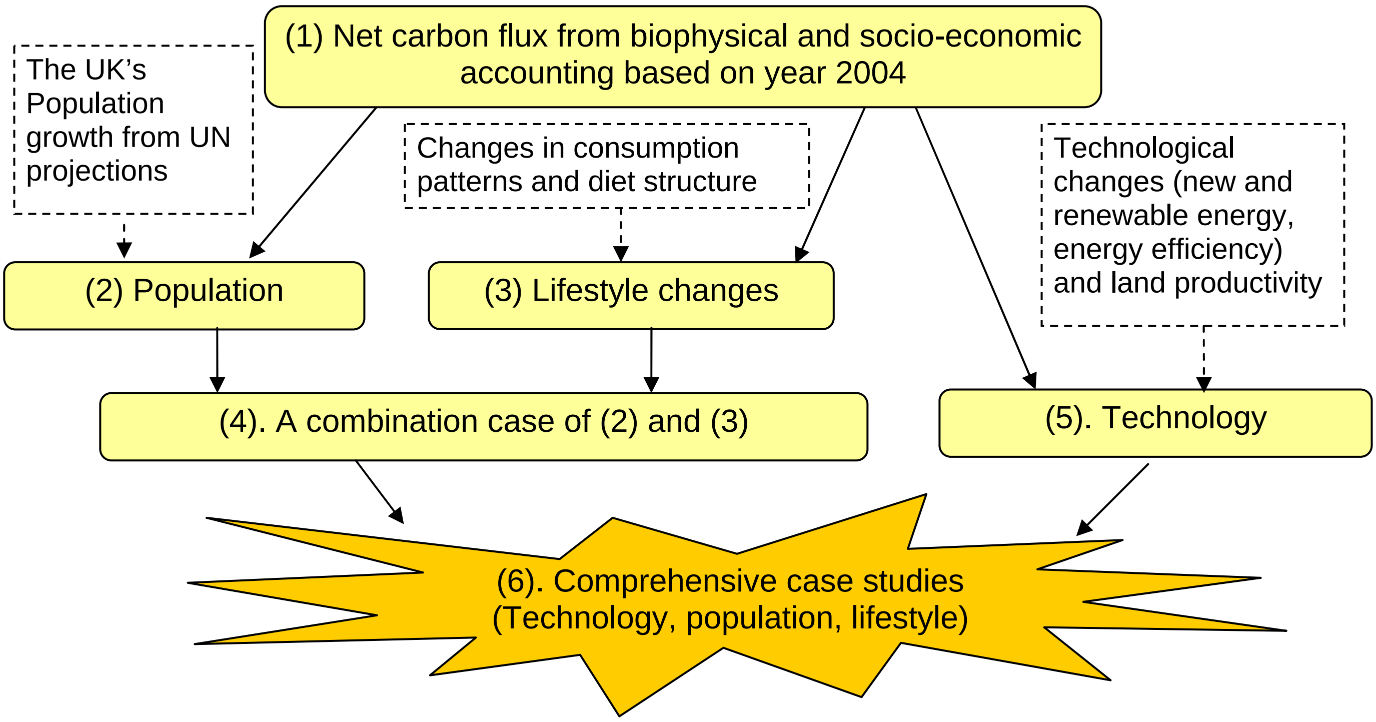
$$C_N = C_P - C_s \qquad \text{Eq. (21)}$$

4.0 SCENARIO ANALYSIS

Input-output analysis provides a framework for organizing quantitative information about production and consumption activities into a database and using it to analyse scenarios about the future. With regards to further understanding of the future changes of net carbon flux, we identify a number of major driving forces including population, consumption and lifestyle changes, and technology, represented by six scenarios (see Figure 2). After establishing scenarios for each of the main driving forces, we introduce them step by step to show the additional effects. Starting from the base year of 2004, a range of scenarios representing the major factors is added to show their additional effects on carbon emissions and carbon sequestrations due to changes of land-uses.

Scenario 1 represents the real situation in the base year 2004 in the UK, with the technology and population, consumption pattern of 2004. In Scenario 2, we add to Scenario 1 final demand changes and additional direct and indirect changes of carbon emission and carbon sequestrations caused by a population of year 2030 based on UN population projection. Scenario 3 includes consumption pattern and lifestyle changes as represented by a set of income elasticities based on basic case of year 2004. Scenario 4 is the combination of case of Scenario 2 and Scenario 3. Scenario 5 applies more advanced technology available in year 2030 to the socio-economic and demographic structure of 2004. Sceonaro 6 is designed to see the overall effects of a combined Scenario 4 and Scenario 5.

Figure 2: Proposed Scenarios



5.0 FUTURE RESEARCH PLAN AND CONCLUSION

At present, this full carbon accounting framework is purely conceptual based research. Therefore, the future applications of this framework will be carried out in the coming years. The main step to make this accounting framework applicable is to collect sufficient data for different types of models, such: sectoral carbon emission data, land-use data, and NPP. Also, there are also a large potential on the further improvement of the models for future research on carbon emission and carbon sequestration issues.

There are currently some of researches working on similar topics, which either focus on carbon emission from industry or carbon sequestration in ecosystem. But none of them is proposing an integrated approach as outlined above. Therefore, this research will be of academic contribution for the literatures of ecological economics studies. Also, this research can help to policy maker on energy consumption and carbon emissions; serve for policy evaluation; and project the future changes of carbon emissions and sequestrations and land-use.

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