Socioeconomic Drivers of Greenhouse Gas Emissions in the United States

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ABSTRACT

Existing studies examined the US's direct GHG emitters and final consumers driving upstream GHG emissions, but overlooked the US's primary suppliers enabling downstream GHG emissions and relative contributions of socioeconomic factors to GHG emission changes from the supply side. This study investigates GHG emissions of sectors in the US from production-based (direct emissions), consumption-based (upstream emissions driven by final consumption of products), and income-based (downstream emissions enabled by primary inputs of sectors) viewpoints. We also quantify relative contributions of socioeconomic factors to the US's GHG emission changes during 1995–2009 from both the consumption and supply sides, using structural decomposition analysis (SDA). Results show that income-based method can identify new critical sectors leading to GHG emissions (e.g., *Renting of Machinery & Equipment and Other Business Activities* and *Financial Intermediation* sectors) which are unidentifiable by production-based and consumption-based methods. Moreover, the supply-side SDA reveals new factors for GHG emission changes: mainly production output structure representing product allocation pattern and primary input structure indicating sectoral shares in primary inputs. In addition to production-side and consumption-side GHG reduction measures, the US should also pay attention to supply-side measures such as influencing the behaviors of product allocation and primary inputs.

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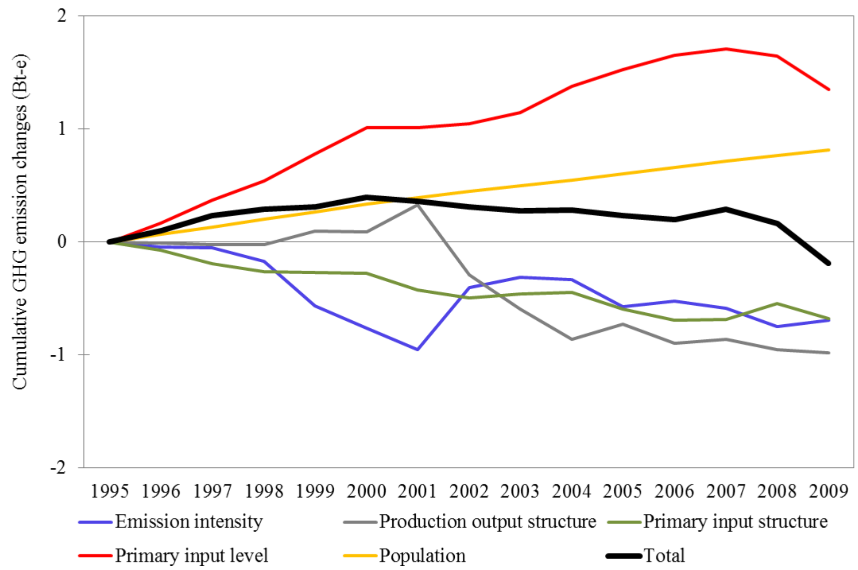


INTRODUCTION

The United States (US) is the world's second largest CO_2 emitter by contributing 15% of global CO_2 emissions in 2011 [1]. It expects to reduce CO_2 emissions by 26% – 28% in 2025 below the 2005 level in the U.S.–China Joint Announcement on Climate Change [2]. Moreover, the US has limited future emission quota based on its population size [3]. Thus, it is urgent for the US to seek effective measures to reduce CO_2 emissions.

Socioeconomic activities have been viewed as major drivers of environmental emissions [4, 5]. Existing studies have investigated how the US's socioeconomic activities lead to its CO_2 emissions, providing the scientific foundation for policy interventions. The Environmental Protection Agency [6] and Department of Energy [7] have been investigating direct GHG emissions in the US. Their studies focus on direct emitters (e.g., economic sectors or production processes) of GHG emissions (a.k.a. production-based emissions), and thereby provide scientific foundations for production-side policymaking such as improving energy usage efficiency and implementing carbon capture and sequestration technologies. On the other hand, economic activities are also driven by consumers through product supply chains (i.e., demand-driven) [8], and production-side measures alone are not adequate to control emissions if the final demand keeps growing [9, 10]. Accounting for GHG emissions from the consumption side, i.e., considering both direct and indirect GHG emissions caused by product consumption (a.k.a. consumption-based emissions), can help policymaking to reduce embodied emission leakage from final consumption to the production [9-18]. To understand how the US's final demand drives its production-side GHG emissions, several studies have evaluated GHG emissions embodied in the final consumption of its products [19, 20]. Moreover, relative contributions of socioeconomic factors to historical changes of the US's GHG emissions from the consumption side are quantified [21, 22].

Economic activities can be seen as not only demand-driven but also supply-driven (i.e., driven by primary suppliers through product sale chains [23-25]). Primary suppliers, by supplying primary inputs in the first place, enable GHG emissions of downstream users through product sale chains (a.k.a. income-based emissions) [26-29]. Revealing critical primary suppliers can help supply-side policymaking to reduce GHG emissions, such as choosing less GHG-intensive downstream users and guiding primary input behaviors (e.g., limiting loan supply and decreasing capital depreciation rates) [30]. This study finds that the supply-side analyses can identify new critical factors leading to the US's GHG emissions (e.g., *Renting of Machinery & Equipment and Other Business Activities* and *Financial Intermediation* sectors, production output structure, and primary input structure) which are unidentifiable in production-side and consumption-side analyses. However, primary suppliers driving the US's GHG emissions are left unknown in existing studies. Moreover, relative contributions of socioeconomic factors to historical changes of the US's GHG emissions from the supply side (e.g., primary input structure, primary input level, and production output structure) are not revealed. Thus, existing studies on the US's GHG emissions cannot support the supply-side policymaking (e.g., influencing product allocation and primary input behaviors).

This study fulfills such knowledge gaps by analyzing socioeconomic drivers of the US's GHG emissions from the supply side. This study first evaluates income-based GHG emissions of sectors during 1995–2009 based on the environmentally extended input-output model and compares income-based results with production-based and consumption-based results. It then quantifies relative contributions of five socioeconomic factors to historical changes of the US's GHG emissions from the supply side during 1995–2009 (including GHG emission intensity, production output structure, primary input structure, primary input level, and population), using structural decomposition analysis [31, 32]. This study also compares relative contributions of socioeconomic factors from the supply side with results from the consumption side. To the best of our knowledge, this is the first comprehensive analysis on socioeconomic drivers of the US's GHG emissions. Results from the supply side in this study provide new insights for the policymaking to reduce the US's GHG emissions.

METHODS AND DATA

Input-output models

An input-output (IO) model describes product transactions within an economy. It comprises sectoral total input vector, primary input vector, intermediate transactions matrix, final demand vector, and sectoral total output vector [8]. It has row and column balances described by equations (1) and (2).

$$x = \mathrm{Z}e + y \qquad (1)$$

$$x' = e'\mathrm{Z} + v \qquad (2)$$

Assume that the economy is divided into n economic sectors. The n×1 column vectors x and y indicate each sector's total output/input (each sector's total output equals to its total input) and final demand, respectively; the 1×n row vector v indicates each sector's primary inputs (including imports, employee compensation, fixed assets depreciation, taxes, and subsidies, etc.); the n×n matrix Z represents product transactions among economic sectors; and e is a n×1 column vector, with each element as one. The notation ' means the transposition.

Defining direct input coefficient matrix A and direct output coefficient matrix B by equations (3) and (4), we can write equations (1) and (2) into the form of equations (5) and (6). The element a_{ij} of matrix A indicates direct input from sector i required to produce unitary output of sector j; the element b_{ij} of matrix B represents direct output of sector *j* enabled by unitary input of sector *i*; matrix I is an identity matrix. The hat ^ means diagonalizing the vector.

$$\mathrm{A} = \mathrm{Z}(\hat{x})^{-1} \tag{3}$$

$$\mathrm{B} = (\hat{x})^{-1}\mathrm{Z} \tag{4}$$

$$x = (\mathrm{I} - \mathrm{A})^{-1} y = \mathrm{L}y \tag{5}$$

$$x' = v(\mathrm{I} - \mathrm{B})^{-1} = v\mathrm{G} \tag{6}$$

The matrix $\mathrm{L} = (\mathrm{I} - \mathrm{A})^{-1}$ is the *Leontief Inverse* matrix [8], the element l_{ij} of which indicates total (direct and indirect) input from sector *i* required to produce unitary final demand of products from sector *j*. The matrix $\mathrm{G} = (\mathrm{I} - \mathrm{B})^{-1}$ is the *Ghosh Inverse* matrix [8], the element g_{ij} of which represents total (direct and indirect) output of sector *j* enabled by unitary primary input of sector *i*.

The Ghosh and Leontief IO models view product flows from two different directions. The Ghosh IO model captures product sale chains (i.e., the allocation of products) and examine where products go to, and the Leontief IO model captures product supply chains (i.e., the use of products) and examine where products come from [33, 34]. It is worth noting that there have been many debates on the interpretation of the Ghosh IO model [34-36]. The Ghosh IO model (regarded as cost-push) is usually interpreted as a price model assuming fixed quantities, and the Leontief IO model (regarded as demand-pull) is usually interpreted as a quantity model assuming fixed prices [34]. The Leontief IO model assumes that final demand is the exogenous driver of output, while the Ghosh IO model assumes that price change of primary inputs (e.g., labor and capital) is the exogenous driver of output [34]. Scholars have recently applied the Ghosh IO model on carbon emission studies [26-30, 32]. Interpreting policy implications of results based on the Ghosh IO model should take into account these debates.

Production-based, consumption-based, and income-based GHG emissions

This study uses the environmentally extended input-output (EEIO) model to evaluate production-based, consumption-based, and income-based GHG emissions of sectors. We construct the EEIO model by treating each sector's direct GHG emissions as the satellite account of the input-output model.

Production-based GHG emissions of sectors (indicated by $1 \times n$ row vector t) mean their direct GHG emissions, which are the satellite account of the EEIO model. Defining a $1 \times n$

intensity vector *f* to represent GHG emissions of each sector for its unitary output, as expressed by equation (7), we can calculate total GHG emissions of an economy *g* by equation (8).

$$f = t(\hat{x})^{-1} \tag{7}$$

$$g = fx = f\mathrm{L}y = v\mathrm{G}f' \tag{8}$$

Consumption-based (expressed by 1×*n* row vector *c*) and income-based (expressed by *n*×1 column vector *s*) GHG emissions of sectors can be calculated by equations (9) and (10), respectively. Consumption-based GHG emissions of a sector mean total (direct and indirect) upstream GHG emissions caused by the final demand of products from this sector. Income-based GHG emissions of a sector indicate total (direct and indirect) downstream GHG emissions enabled by primary inputs of this sector.

$$c = f\mathrm{L}\hat{y} \tag{9}$$

$$s = \hat{v}\mathrm{G}f' \tag{10}$$

Structural decomposition analysis

We use the structural decomposition analysis (SDA) to investigate relative contributions of economic factors to GHG emission changes [31, 32]. We further decompose *y* and *v* in equation (8) into the following forms

$$y = \mathrm{Y_s} y_l p \tag{11}$$

$$v = p v_l \mathrm{V_s} \tag{12}$$

where matrix $\mathrm{Y_s}$ stands for final demand structure (i.e., percentage share of each sector in each category of final demand); vector y_l indicates per capita final demand volume (i.e., final demand level); *p* represents the population; v_l stands for per capita primary input volume (i.e., primary input level); and $\mathrm{V_s}$ represents primary input structure (i.e., percentage share of each sector in each category of primary inputs). Final demand categories in this study include final consumption expenditure by households, final consumption expenditure by non-profit organizations serving households, final consumption expenditure by government, gross fixed capital formation, changes in inventories and valuables, and exports. Primary input categories in this study include value added at basic prices, international transport margins, and imports.

Equation (8) can then be written as the following forms:

$$g = f\mathrm{LY_s}y_l p \tag{13}$$

$$g = pv_l\mathrm{V_s}\mathrm{G}f' \tag{14}$$

Equation (13) views the economy as demand-driven, while equation (14) views the economy as supply-driven. Decomposition forms of these two equations are shown in equations (15) and (16).

$$\Delta g = \Delta f\mathrm{LY_s}y_l p + f\Delta\mathrm{LY_s}y_l p + f\mathrm{L}\Delta\mathrm{Y_s}y_l p + f\mathrm{LY_s}\Delta y_l p + f\mathrm{LY_s}y_l\Delta p \tag{15}$$

$$\Delta g = \Delta p v_l\mathrm{V_s}\mathrm{G}f' + p\Delta v_l\mathrm{V_s}\mathrm{G}f' + pv_l\Delta\mathrm{V_s}\mathrm{G}f' + pv_l\mathrm{V_s}\Delta\mathrm{G}f' + pv_l\mathrm{V_s}\mathrm{G}\Delta f' \tag{16}$$

Items in the right side of equation (15) represent relative contributions of emission intensity change Δf, production input structure change $\Delta\mathrm{L}$, final demand structure change $\Delta\mathrm{Y_s}$, final demand level change Δy_l, and population change Δp to GHG emission change of an economy Δg (in the left side). Similarly, items in the right side of equation (16) represent relative contributions of emission intensity change Δf, production output structure change $\Delta\mathrm{G}$, primary input structure change $\Delta\mathrm{V_s}$, primary input level change Δv_l, and population change Δp to GHG emission change of an economy Δg (in the left side).

It is worth noting that we convert all IO data into constant prices for the SDA, which can avoid the effect of price changes. Thus, the Leontief IO-SDA model assumes that quantity change in final demand and components is the exogenous driver of output and emissions, while the Ghosh IO-SDA model assumes that quantity change in the supply of primary inputs, instead of price change of primary inputs, is the exogenous driver of output and emissions.

The SDA has the non-uniqueness problem: decomposing into *n* factors produces *n*! types of decomposition forms [37]. To solve this problem, we use the average of all possible first-order decomposition results as the relative contribution of each factor in this study [38], as widely done in previous studies [22, 37, 39-53]. It is worth noting that the SDA assumes mutual independence among decomposed factors [44, 54], which is not fully consistent with practical situation. Addressing this pervasive problem for decomposition methods is an interesting future research avenue.

Data sources

This study requires three types of data: monetary input-output tables (MIOTs), GHG emissions of sectors, and the population of the US. We collect MIOTs and GHG emission data from the World Input-Output Database (WIOD, released in November 2013) which is in 35-sector format and covers the time period of 1995–2009 [55-57]. We choose these data from the WIOD given its relatively detailed sector classification, long temporal coverage, and the availability of price indices. There are also other sources of similar data, such as the US Bureau of Economic Analysis (BEA) [58], GTAP [59], EXIOBASE [60], and Eora [61]. Although the BEA publishes high-resolution MIOTs (in 71-sector format) each year [58], GHG emission data from the US statistics are highly aggregated, only classified as 6 sectors including agriculture, industry, electricity generation, transportation, commercial, and residential sectors [6]. The other three databases are either with limited time points or without price indices, which limits the implementation of SDA based on comparable MIOTs. GHG emissions in this study include CO_2, CH_4, and N_2O emissions. These three kinds of GHG emissions are all weighted to CO_2 equivalents, and their CO_2 equivalent weighting factors are from the Intergovernmental Panel on Climate Change (IPCC) [62]. The US's population data come from the World Bank [1].

The WIOD has lower sector resolution than other databases such as Eora and BEA. Sector aggregation can, to some extent, affect sectoral results in IO studies [63-67]. Developing a US database with higher sector resolution, time-series MIOT and GHG data for a long time period, and time-series price indices is an interesting future research avenue.

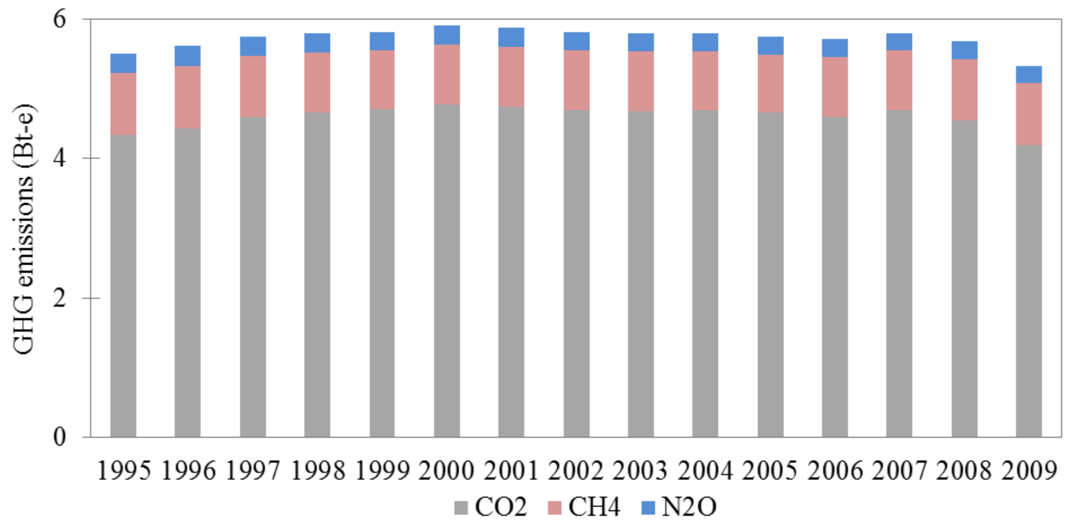
In particular, we use the US's current-year-price MIOTs to calculate consumption-based and income-based GHG emissions of sectors for each year, while constant-price MIOTs to conduct the SDA. The WIOD contains current-year-price (released in November 2013) and previous-year-price (released in December 2014) MIOTs for each year [55, 57]. We conduct the SDA for annual changes of the US's GHG emissions during 1995–2009 based on these two types of MIOTs (e.g., using 2009 MIOT in 2008-year price and 2008 MIOT in current-year price for the SDA between 2008 and 2009). The contribution of a decomposed factor between any two time points equals to the sum of its annual contributions during this period [68].

This study finds that exports contribute 10% of the US's GHG emissions from the consumption side and imports contribute 10% from the supply side. We only concern domestic supply chains of the US in this study. It is an interesting research avenue to investigate socioeconomic drivers of the US's GHG emissions in the context of global supply chains, which can well capture international feedback effect from international trade.

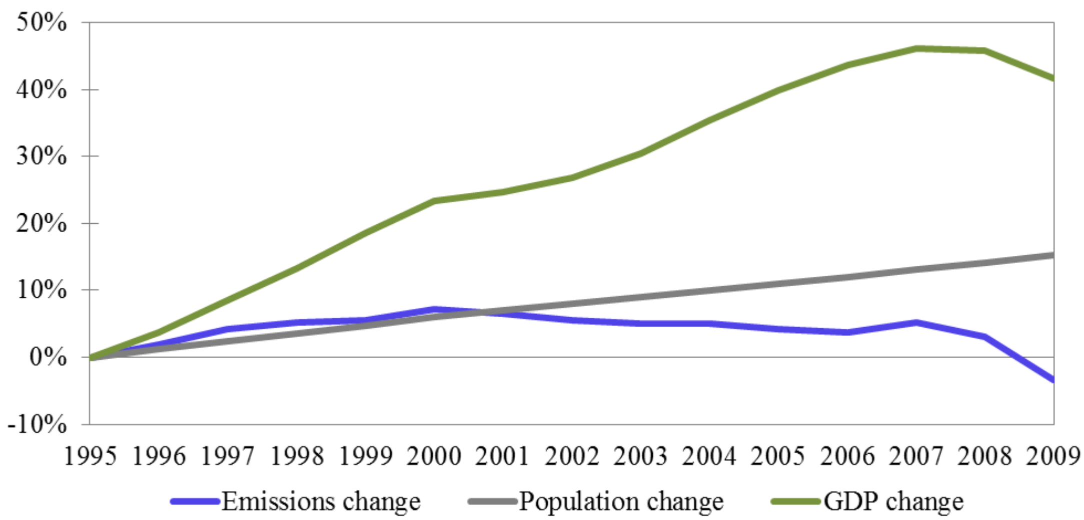
RESULTS

Variation trend in GHG emissions of the US

The US's industrial system discharged 5.3 billion tonne CO_2 equivalents (Bt-e) of GHG emissions in 2009, 3% lower than its 1995 level (Figure 1A). CO_2 is the dominant component of the US's GHG emissions, accounting for 79% of GHG emissions in 2009. The US's GHG emissions keep relatively stable during 1995–2009, with slightly increasing trends during 1995–2000 (from 5.5 to 5.9 Bt-e) and 2006–2007 (from 5.7 to 5.8 Bt-e) and slightly decreasing trends during 2000–2006 (from 5.9 to 5.7 Bt-e) and 2007–2009 (from 5.8 to 5.3 Bt-e). Meanwhile, the US's gross domestic product (GDP, in constant 2011 international $) and population increased by 42% and 15%, respectively, during 1995–2009 (Figure 1B) [1]. Thus, the US has achieved absolute decoupling for GHG emissions in this period.



(A) Changes in industrial GHG emissions



(B) Decoupling trends among GHG emissions, GDP, and population

Figure 1. Changes in industrial GHG emissions (A) and GDP and population (B) in the US during 1995–2009. Values in Figure B indicate percentage changes relative to

amounts in 1995. Full data supporting this graph are listed in Table S1 in the Supporting Information (SI).

GHG emissions of sectors in 2009

Figure 2 shows the US's GHG emissions at the sector level in 2009. The *Electricity, Gas and Water Supply* sector, which is a major energy user, is the largest contributor to GHG emissions in the US. It directly discharged 2.1 Bt-e of GHG emissions, accounting for 39% of the national total in 2009. Its consumption-based (1.1 Bt-e) and income-based GHG emissions (1.6 Bt-e) are 47% and 21% lower than its production-based GHG emissions, respectively. Its income-based GHG emissions are 48% higher than its consumption-based emissions in 2009, indicating its important role as a primary supplier to economic production and GHG emissions of downstream users. We observe similar situation for *Agriculture, Hunting, Forestry and Fishing* and *Inland Transport* sectors.

The *Mining and Quarrying, Renting of Machinery & Equipment and Other Business Activities, Financial Intermediation,* and *Wholesale Trade and Commission Trade (Except of Motor Vehicles and Motorcycles)* sectors have much higher income-based GHG emissions than their production-based and consumption-based GHG emissions in 2009. For example, income-based GHG emissions of *Renting of Machinery & Equipment and Other Business Activities* sector are 321% and 419% higher than its production-based and consumption-based GHG emissions, respectively. Moreover, income-based GHG emissions of *Financial Intermediation* sector are 568% and 154% higher than its production-based and consumption-based GHG emissions, respectively. This finding indicates that these sectors are more important as primary suppliers driving downstream GHG emissions than as direct emitters and final consumers.

In addition, *Public Administration and Defence & Compulsory Social Security, Other Community, Social and Personal Services, Health and Social Work,* and *Air Transport* sectors have much lower income-based GHG emissions than their production-based and consumption-based GHG emissions in 2009. For example, income-based GHG emissions of *Air Transport* sector are 48% and 44% lower than its production-based and consumption-based GHG emissions, respectively. These sectors are less important as primary suppliers than as direct emitters and final consumers for responsibilities for GHG emissions.

In general, income-based method reveals much different GHG emission profile of sectors in the US, which cannot be revealed by production-based and consumption-based methods.

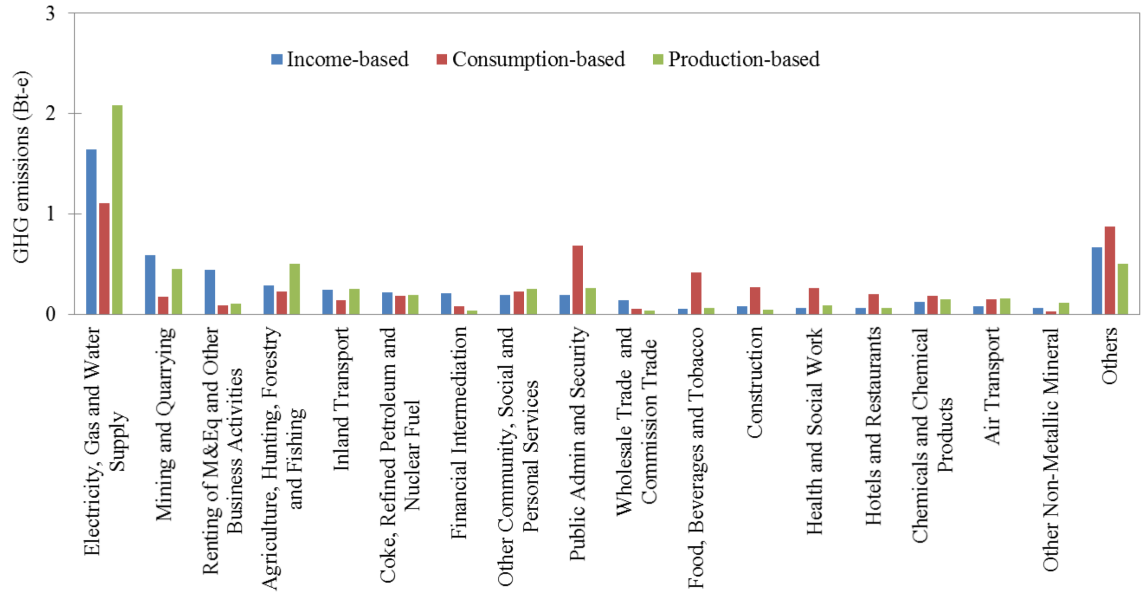
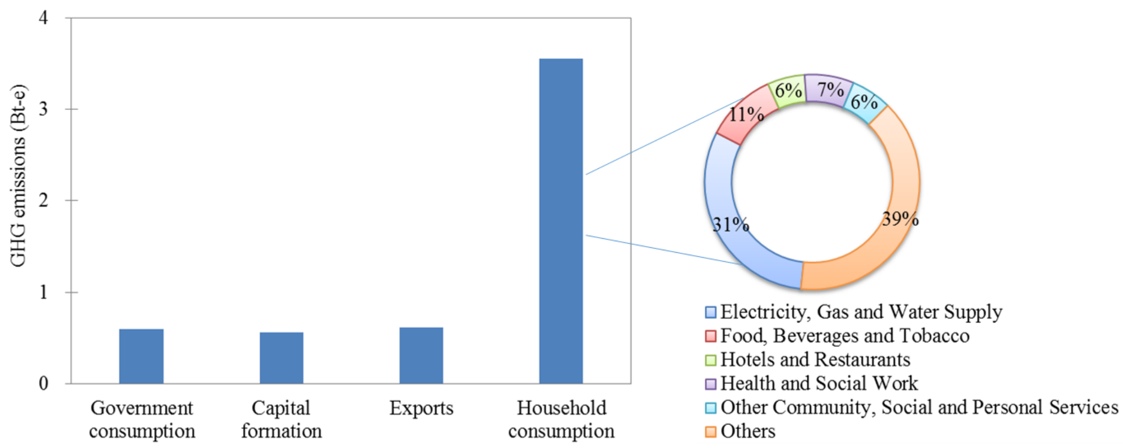


Figure 2. Income-based, consumption-based, and production-based GHG emissions of sectors in the US in 2009. Full data supporting this graph are listed in Table S2 in the SI.

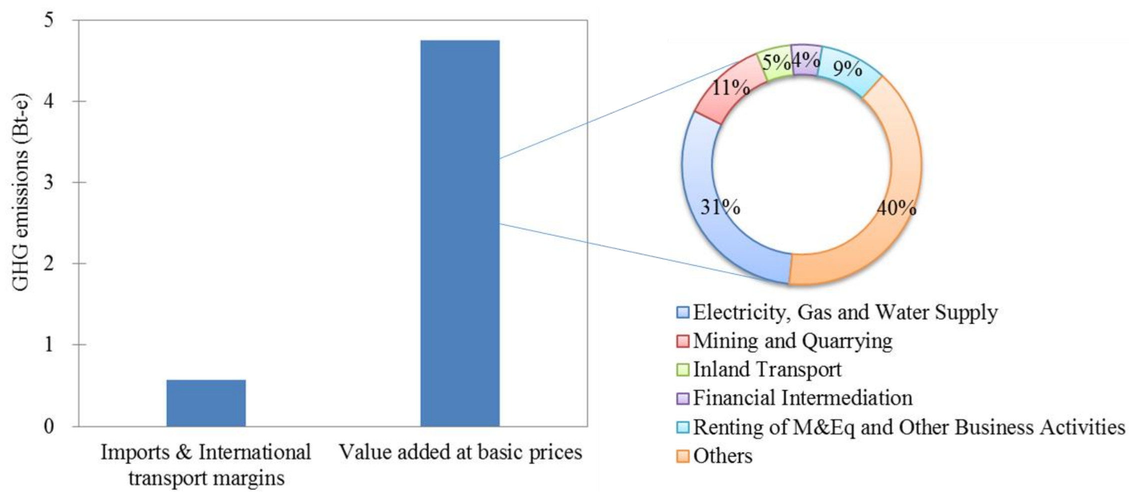
Figure 3 further disaggregates GHG emissions of the US by final demand and primary input categories. On the consumption side, household consumption is the major driver, contributing 67% of GHG emissions in the US in 2009. Thus, GHG reduction measures of the US should pay special attention to domestic final consumption. In particular, these GHG emissions are mainly caused by the consumption of products from *Electricity, Gas and Water Supply*, *Food, Beverages and Tobacco*, *Hotels and Restaurants*, *Health and Social Work*, and *Other Community, Social and Personal Services* sectors by households (Figure 3A). Exports only lead to 10% of the US's GHG emissions in 2009. Exports of the US are shifting from products of *Electrical and Optical Equipment* and *Wholesale Trade and Commission Trade* sectors to products of *Financial Intermediation*, *Renting of Machinery & Equipment and Other Business Activities*, and *Coke, Refined Petroleum and Nuclear Fuel* sectors (Figure S1A). The US should also pay attention to GHG reductions in upstream suppliers of these three latter sectors.

On the supply side, domestic value-added creation is the major contributor by leading to 89% of the US's GHG emissions in 2009. Such part of GHG emissions are mainly due to domestic value-added creation in *Electricity, Gas and Water Supply*, *Mining and Quarrying*, *Inland Transport*, *Financial Intermediation*, and *Renting of Machinery & Equipment and Other Business Activities* sectors (Figure 3B). Thus, GHG reduction measures of the US should pay special attention to domestic value-added creation in these sectors. Imports only lead to 10% of the US's GHG emissions in 2009. Imports of the US are shifting from *Transport Equipment*, *Electrical and Optical Equipment*, and *Basic Metals and Fabricated Metal* sectors to *Coke, Refined Petroleum and Nuclear*

Fuel, *Public Administration and Defence & Compulsory Social Security*, and *Financial Intermediation* sectors (Figure S1B) which have relatively high income-based GHG emissions (Figure 2). Thus, the US governments should also pay close attention to GHG reductions in downstream users of these three latter sectors.



(A) By final demand categories



(B) By primary input categories

Figure 3. GHG emissions of the US by final demand and primary input categories in 2009. Full data supporting this graph are listed in Table S3 in the SI.

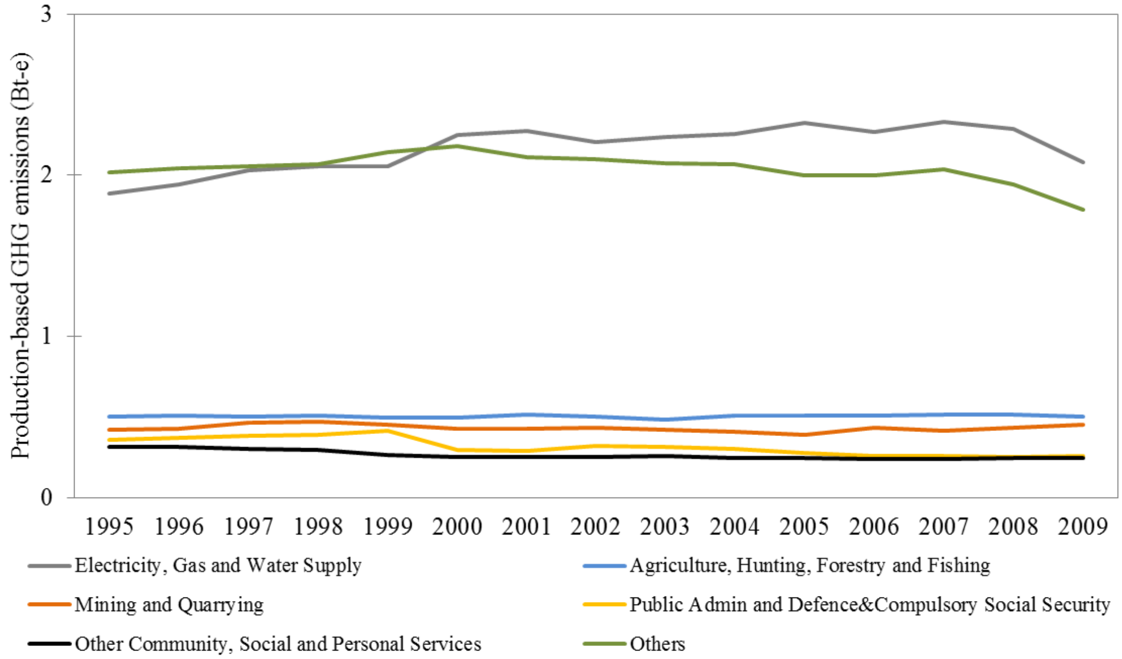
Evolution of GHG emissions of sectors during 1995–2009

Figure 4 shows evolution trends in GHG emissions of sectors during 1995–2009. Major direct GHG emitters in the US during 1995–2009 are *Electricity, Gas and Water Supply*, *Agriculture, Hunting, Forestry and Fishing*, *Mining and Quarrying*, *Public Administration and Defence & Compulsory Social Security*, and *Other Community,* *Social and Personal Services* sectors (Figure 4A). Direct GHG emissions of the *Electricity, Gas and Water Supply* sector gradually increased from 1.9 Bt-e in 1995 to 2.3 Bt-e in 2007, and then decreased to 2.1 Bt-e in 2009 potentially due to the shock of global financial crisis. Direct GHG emissions of *Public Administration and Defence & Compulsory Social Security* and *Other Community, Social and Personal Services* sectors show generally decreasing trends during 1995–2009. Moreover, direct GHG emissions of the other two sectors keep relatively stable in this time period.

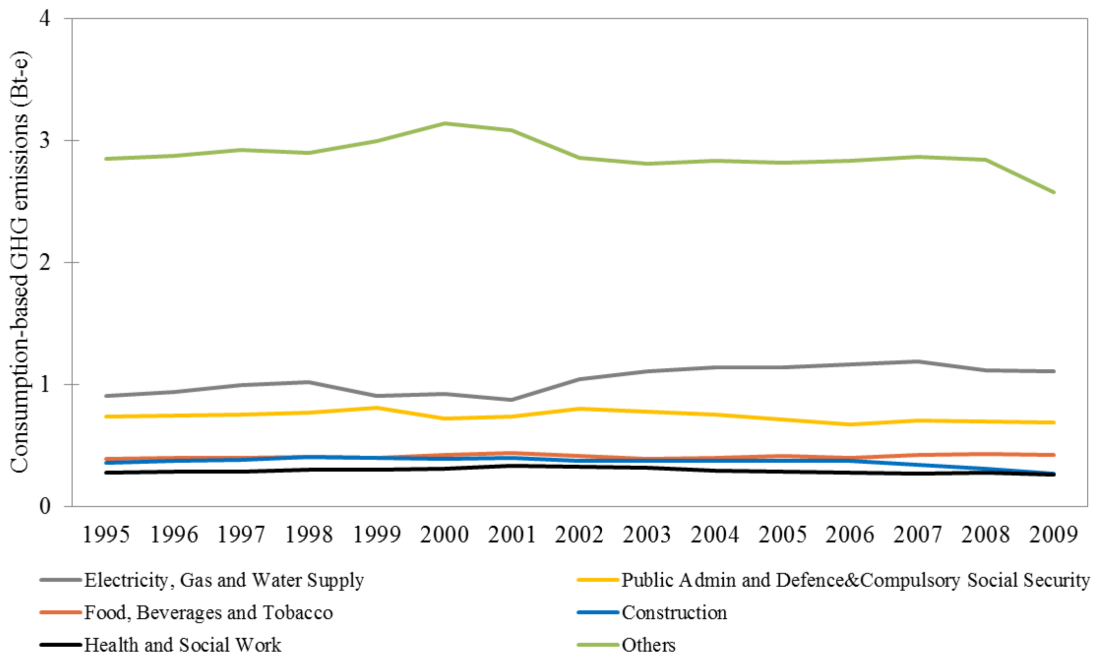
The final demand of products of the *Electricity, Gas and Water Supply, Public Administration and Defence & Compulsory Social Security*, *Food, Beverages and Tobacco*, *Construction*, and *Health and Social Work* sectors are main drivers of upstream GHG emissions in the US during 1995–2009 (Figure 4B). Consumption-based GHG emissions of the *Electricity, Gas and Water Supply* sector increased during 1995–1998 (from 0.9 to 1.0 Bt-e) and 2001–2007 (from 0.9 to 1.2 Bt-e), while decreased during 1998–2001 (from 1.0 to 0.9 Bt-e) and 2007–2009 (from 1.2 to 1.1 Bt-e). Consumption-based GHG emissions of the other four sectors keep relatively stable during 1995–2009.

The primary inputs of *Electricity, Gas and Water Supply*, *Mining and Quarrying*, *Renting of Machinery & Equipment and Other Business Activities, Agriculture, Hunting, Forestry and Fishing,* and *Financial Intermediation* sectors are the main factors that enable downstream GHG emissions in the US during 1995–2009 (Figure 4C). Income-based GHG emissions of the *Electricity, Gas and Water Supply* sector remained stable during 1995–1998, and then suddenly decreased during 1998–2001. Its income-based GHG emissions began to increase after 2001, but subsequently decreased in 2005, 2008, and 2009. The *Financial Intermediation* and *Renting of Machinery & Equipment and Other Business Activities* sectors first have an increasing trend during 1995–2001, and then a decreasing trend during 2001–2009 for their income-based GHG emissions. Moreover, income-based GHG emissions of *Mining and Quarrying* sector show a slightly increasing trend during 1995–2009, while that of the *Agriculture, Hunting, Forestry and Fishing* sector remain relatively stable in this period.

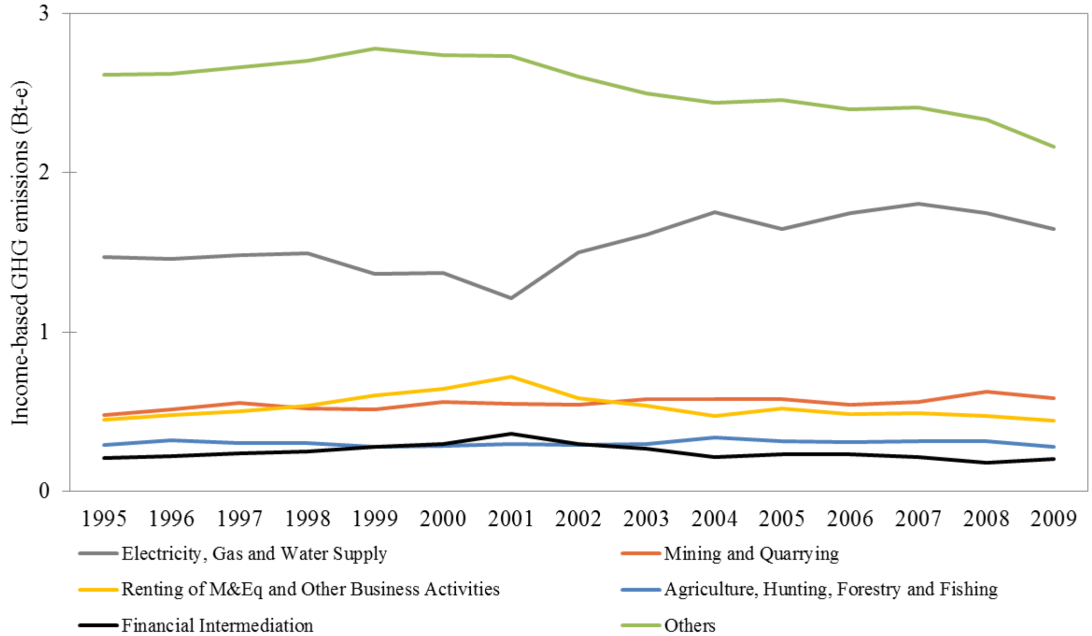
Income-based method reveals new variation trend for GHG emissions of the *Electricity, Gas and Water Supply* sector. Although production-based and consumption-based GHG emissions of the *Electricity, Gas and Water Supply* sector in 2005 increased by 3% over and stayed the same as the 2004 level, respectively, its income-based GHG emissions decreased by 6% than the 2004 level. Income-based method also identifies the importance of *Financial Intermediation* and *Renting of Machinery & Equipment and Other Business Activities* sectors in the US's GHG emissions during 1995–2009, a fact that is unidentifiable by production-based and consumption-based methods.



(A) Production-based GHG emissions of sectors



(B) Consumption-based GHG emissions of sectors



(C) Income-based GHG emissions of sectors

Figure 4. Variation trends of GHG emissions of sectors in the US during 1995–2009. Full data supporting this graph are listed in Tables S4-1 to S4-3 in the SI.

Key drivers of overall GHG emission changes during 1995–2009

Changes in GHG emissions are influenced by many socioeconomic factors, such as population, technology improvement, and structural changes. We use the SDA to analyze relative contributions of socioeconomic factors to changes in the US's GHG emissions during 1995–2009 from both the consumption and supply sides.

From the consumption side (Figure 5A), the increase in final demand level (i.e., final demand volume for per capita) is the largest driver leading to the increase of GHG emissions in the US during 1995–2009. Final demand level of the US increased by 28% in this period, contributing 1.4 Bt-e of GHG emission increments if other factors remain constant. The population of the US increased by 15% during 1995–2009. It is the second factor driving the increase of GHG emissions in the US, contributing 0.8 Bt-e of GHG emission increments if other factors remain constant in this period.

The change in production input structure is the major force reducing GHG emissions in the US during 1995–2009. Technology innovation in this period improves production efficiency of sectors (i.e., using less upstream inputs to produce unitary output), reducing 1.2 Bt-e of GHG emissions if other factors remain constant.

The change in GHG emission intensity is the second force reducing GHG emissions in the US during 1995–2009. GHG emission intensity of most sectors decreases in this period (Table S7), mainly due to the reduction of energy intensity and the shifting of energy mix from coal to natural gas [22]. The reduction of GHG emission intensity contributed 0.7 Bt-e of GHG emission reductions during 1995–2009 if other factors remain constant.

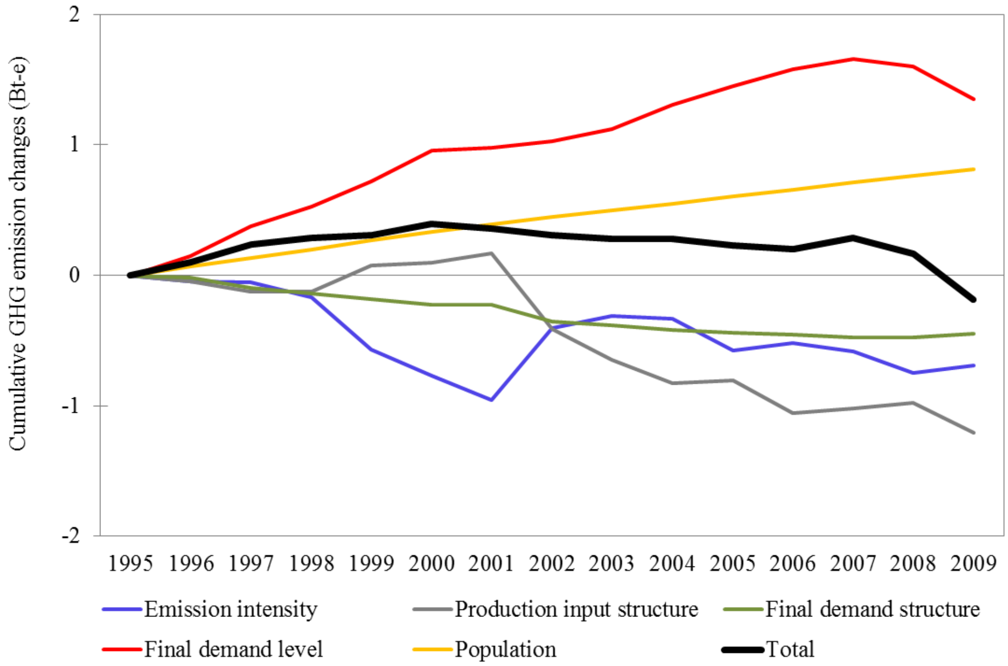
Final demand structure change is also another force reducing GHG emissions in the US during 1995–2009. However, its effect on GHG emission reductions is relatively small and remains nearly zero in recent years. Final demand structure of the US gradually shifts from manufactured goods to services during 1995–2009 [22], leading to 0.5 Bt-e of GHG emission reductions in this period if other factors remain constant.

We also reveal relative contributions of socioeconomic factors to the US's GHG emission changes from the supply side (Figure 5B). The change in primary input level (i.e., primary input volume for per capita) is the largest contributor to GHG emission increments in the US during 1995–2009. Primary input level of the US increased by 28% in this period, contributing 1.3 Bt-e of GHG emission increments if other factors remain constant. In addition, population growth is the other driver for the increase of GHG emissions in the US, contributing 0.8 Bt-e of GHG emission increments during 1995–2009 if other factors remain constant in this period.

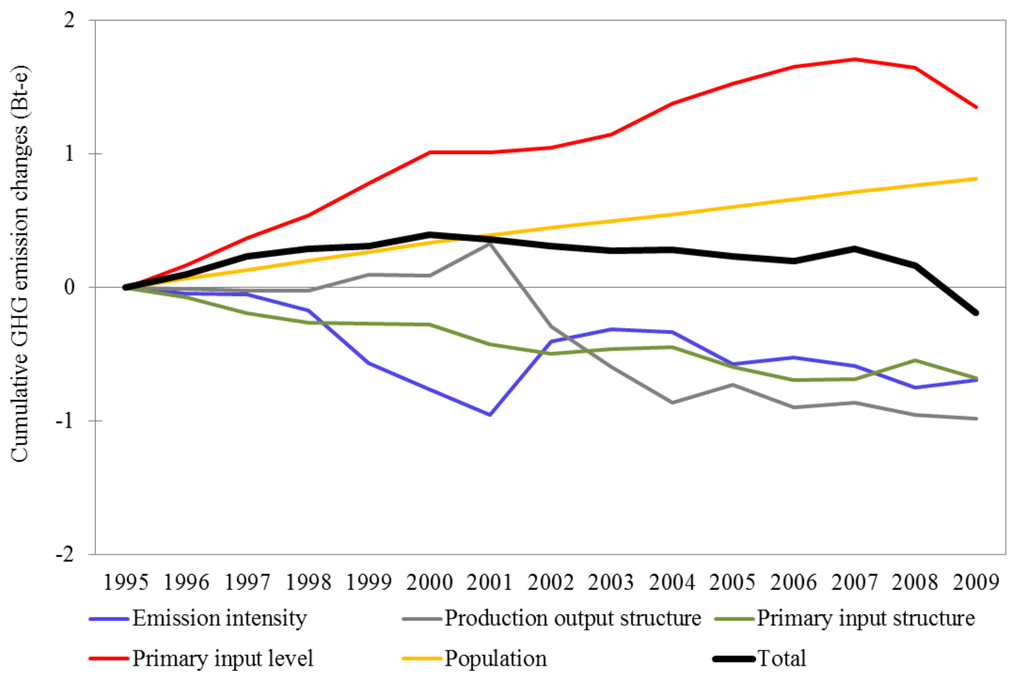
Production output structure represents the allocation pattern of products from each sector. It is the major force reducing GHG emissions in the US during 1995–2009, contributing 1.0 Bt-e of GHG reductions in this period if other factors remain constant. Emission intensity change and primary input structure change are another two factors leading to GHG reductions in the US during 1995–2009. They have the same cumulative contribution of 0.7 Bt-e of GHG reductions in this period if other factors remain constant.

On one hand, the SDA from the supply side uncovers the same results as the SDA from the consumption side. For example, we observe that relative contributions and variation trends of emission intensity and population changes are the same from both the consumption and supply sides. Moreover, we find the same variation trend for final demand level change and primary input level change which both represent the affluence growth. Such findings validate the reliability of the SDA from the supply side.

On the other hand, the supply side reveals additional critical socioeconomic factors as well as their variation trends in addition to those from the consumption side. For example, we observe that production input structure change is the largest force reducing GHG emissions from the consumption side during 1995–1997, while primary input structure change is the largest contributor to GHG emission reductions from the supply side in this period. Cumulative contribution of final demand structure change is smaller than that of emission intensity change during 2005–2007, while cumulative contribution of primary input structure is larger than that of emission intensity change in this period. Thus, the SDA from the supply side can provide new findings to support GHG reduction policymaking in the US.



(A) From the consumption side



(B) From the supply side

Figure 5. Relative contributions of socioeconomic factors to the US's GHG emission changes from the consumption (A) and supply (B) sides during 1995–2009. The baseline year is 1995. Full data supporting this graph are listed in Table S5 in the SI.

Key drivers of GHG emission changes for four typical stages

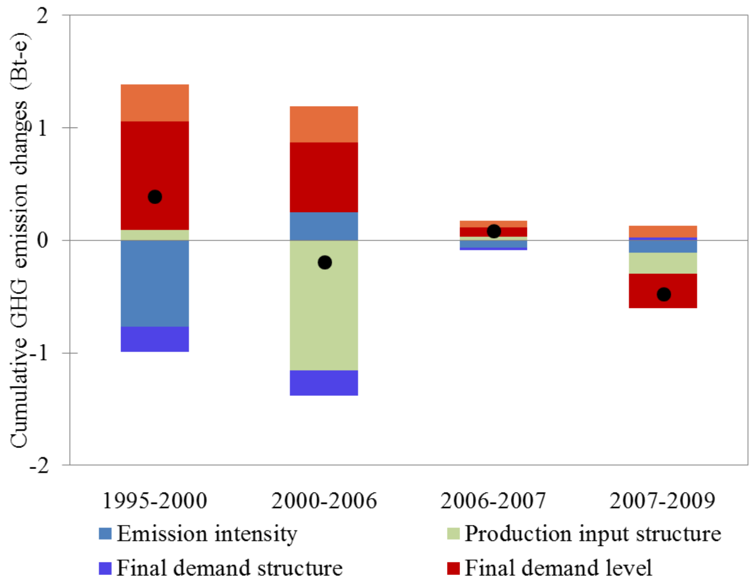
Figures 1 and 5 show that GHG emission changes in the US can be classified into four typical stages: 1995–2000, 2000–2006, 2006–2007, and 2007–2009. We specially investigate relative contributions of socioeconomic factors to changes in the US's GHG emissions from the consumption and supply sides for these four stages, as shown in Figure 6.

GHG emissions in the US increased from 5.5 Bt-e in 1995 to 5.9 Bt-e in 2000. The growth of final demand level, primary input level, and the population and the change in production input/output structure lead to the increase of GHG emissions in this period, while the changes in emission intensity, final demand structure, and primary input structure are major forces reducing GHG emissions. In particular, the effect of production input/output structure change on GHG emission changes is small in this period. GHG emission intensity reduction is the largest force reducing GHG emissions during 1995 – 2000. It mainly happens in three sectors: *Electricity, Gas and Water Supply* sector; *Agriculture, Hunting, Forestry and Fishing;* and the *Other Community, Social and Personal Services* sectors. Their GHG emission intensity in 2000 decreased by 14%, 12%, and 34%, respectively, compared to their 1995 levels (Table S7). Such a decrease benefits from the energy mix shifting from coal to natural gas in this period. The share of coal in electricity generation decreased from 52% in 1995 to 50% in 2000, while the portion of natural gas increased from 11% to 14% [56].

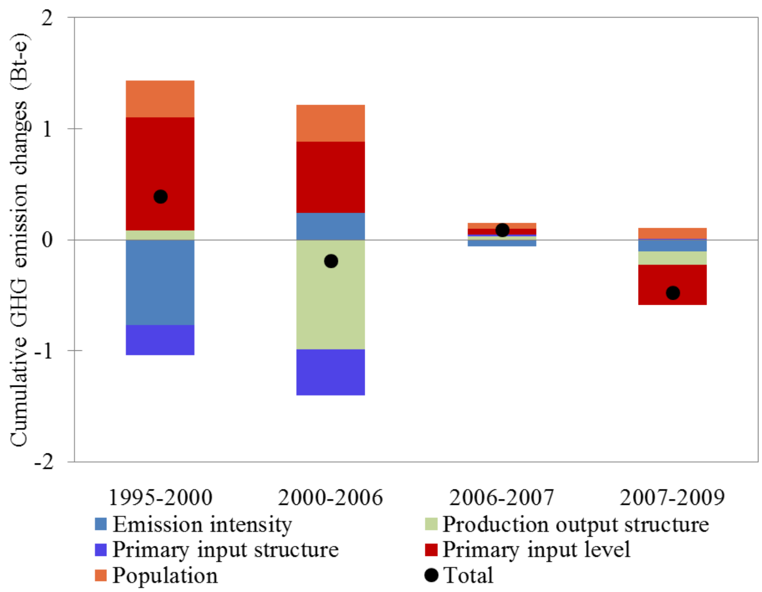
GHG emissions in the US decreased from 5.9 Bt-e in 2000 to 5.7 Bt-e in 2006, but still higher than the 1995 level. The growth of final demand level, primary input level, population, and emission intensity drives the increase in GHG emissions in this period, while changes in production input/output structure, final demand structure, and primary input structure contribute to the reduction of GHG emissions. It is worth noting that we observe interesting patterns for emission intensity change and production input/output structure change during 2000–2006. Emission intensity change in this period contributes to GHG emission increments, which is much different from its effects in other periods. Although GHG emission intensity of most sectors decreased in this period, that of the *Electricity, Gas and Water Supply* sector increases by 42% (Table S7) mainly due to the increase in its energy consumption for unitary output [22]. Production input/output structure change is the most important factor reducing GHG emissions during 2000–2006, while its effect is relatively small in other periods.

GHG emissions in the US increased from 5.7 Bt-e in 2006 to 5.8 Bt-e in 2007. GHG emission intensity change contributes to reducing GHG emissions during 2006–2007, while the growth of primary input level, final demand level, and population and the change in production input/output structure are major forces increasing GHG emissions in this period. In particular, final demand structure change (from the consumption side) in this period leads to GHG emission reductions, but primary input structure change (from the supply side) causes GHG emission increments in this period.

GHG emissions in the US decreased from 5.8 Bt-e in 2007 to 5.3 Bt-e in 2009, probably due to the economic recession in global financial crisis. The reduction in final demand level, primary input level, and GHG emission intensity (Table S7) and the change in production input/output structure are major forces recuing GHG emissions during 2007–2009. On the contrary, population growth and changes in final demand structure and primary input structure lead to GHG emission increments in this period.



(A) From the consumption side



(B) From the supply side

Figure 6. Relative contributions of socioeconomic factors to the US's GHG emission changes from the consumption (A) and supply (B) sides during 1995–2000, 2000–2006, 2006–2007, and 2007–2009. Full data supporting this graph are listed in Table S6 in the SI.

DISCUSSION

This study analyzed production-based, consumption-based, and income-based GHG emissions of sectors, and conducted consumption-side and supply-side SDA to investigate relative contributions of socioeconomic factors. We find that the income-based method and supply-side SDA reveals additional facts to support the US's GHG reduction policymaking.

The US will continue to pursue better life quality, leading to higher final demand level and primary input level. Its population is also expected to grow in the near future. Thus, increasing final demand level, primary input level, and population in the future will continue to push up GHG emissions of the US. On the other hand, the US can take actions in these directions to reduce its GHG emissions: GHG emission intensity, production input/output structure, final demand structure, and primary input structure.

First, reducing GHG emission intensity of sectors can significantly help reduce the US's GHG emissions. Measures include improving energy usage efficiency, shifting the energy mix from coal to less carbon-intensive energy sources (e.g., natural gas and nuclear power), and implementing carbon capture and sequestration (CCS) technologies. These actions should mainly focus on critical sectors with large production-based GHG emissions, such as *Electricity, Gas and Water Supply*, *Agriculture, Hunting, Forestry and Fishing*, *Mining and Quarrying*, *Public Administration and Defence & Compulsory Social Security*, and *Other Community, Social and Personal Services* sectors (Figure 4A). In particular, special attention should be paid to the *Electricity, Gas and Water Supply* sector. It is the largest direct GHG emitter (Figure 2), and its GHG emission intensity increase during 2000–2006 partly leads to GHG emission increments in this period (Figure 6).

Second, changing production structure also contributes to reducing the US's GHG emissions. We find that production input/output structure change has large influence on GHG emission changes (Figure 5). Production input structure (i.e., production structure from the consumption side) describes total upstream inputs required to produce unitary finally used products [8], representing production efficiency of sectors. Improving production efficiency of sectors (i.e., using less upstream inputs to produce the same output [9, 69-71]) can directly and indirectly help reduce GHG emissions of upstream sectors. This action should mainly focus on critical sectors with large consumption-based GHG emission, such as *Electricity, Gas and Water Supply*, *Public Administration and Defence & Compulsory Social Security*, *Food, Beverages and Tobacco, Construction*, and *Health and Social Work* sectors (Figure 4B).

On the other hand, production output structure (i.e., production structure from the supply side) describes total downstream outputs enabled by unitary primary input of particular sectors [8], indicating the allocation pattern of products from upstream sectors. Encouraging sectors to choose less GHG-intensive downstream users can help reduce downstream GHG emissions. This action should pay special attention to critical sectors with large income-based GHG emissions, such as *Electricity, Gas and Water Supply*, *Mining and Quarrying*, *Renting of Machinery & Equipment and Other Business Activities*, *Agriculture, Hunting, Forestry and Fishing*, and *Financial Intermediation* sectors (Figure 4C).

Third, the effect of final demand structure change on GHG reductions remains relatively stable after 2002 (Figure 5A), indicating that there is probably large potential to change final demand structure for GHG reductions in the US. Household consumption is the dominant final demand category leading to GHG emissions (Figure 3A). Thus, changing domestic household consumption behaviors (e.g., encouraging consumers to use less GHG-intensive products by life cycle eco-labeling certification and economic tools) can help reduce the US's GHG emissions, especially the household consumption behaviors on products from *Electricity, Gas and Water Supply*, *Food, Beverages and Tobacco*, *Hotels and Restaurants*, *Health and Social Work*, and *Other Community, Social and Personal Services* sectors (Figure 3A).

Last but not least, the change in primary input structure, indicating the change in sectoral shares of the quantity of primary inputs (e.g., labor and capital), is also a factor influencing the US's GHG emissions. The US governments should encourage enterprises to trace GHG emissions of their downstream users and compile income-based GHG emission reports, especially enterprises in *Electricity, Gas and Water Supply*, *Mining and Quarrying*, *Inland Transport*, *Financial Intermediation*, and *Renting of Machinery & Equipment and Other Business Activities* sectors (Figure 3B). The US governments can use these reports to guide the development of these enterprises by supply-side measures (e.g., controlling loan supply, limiting subsidies, and decreasing depreciation rates of fixed assets by extending their service life [30]).

We find that the supply-side SDA can complement the consumption-side SDA to identify critical socioeconomic factors influencing GHG emission changes. Moreover, income-based method can complement production-based and consumption-based methods to identify critical sectors leading to GHG emissions. Although this study focuses on GHG emissions of the US, this analytical framework is applicable to other indicators (e.g., water use, biodiversity, and employment) and other nations.

SUPPORTING INFORMATION

The supporting information provides detailed data supporting the main text.

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