The human carbon budget: an estimate of the spatial distribution of metabolic carbon consumption and release in the United States

**Tristram O. West · Gregg Marland ·
Nagendra Singh · Budhendra L. Bhaduri ·
Adam B. Roddy**

Abstract Carbon dioxide is taken up by agricultural crops and released soon after during the consumption of agricultural commodities. The global net impact of this process on carbon flux to the atmosphere is negligible, but impact on the spatial distribution of carbon dioxide uptake and release across regions and continents is significant. To estimate the consumption and release of carbon by humans over the landscape, we developed a carbon budget for humans in the United States. The budget was derived from food commodity intake data for the US and from algorithms representing the metabolic processing of carbon by humans. Data on consumption, respiration, and waste of carbon by humans were distributed over the US using geospatial population data with a resolution of $\sim 450 \times 450$ m. The average adult in the US contains about 21 kg C and consumes about 67 kg C year^{-1} which is balanced by the annual release of about 59 kg C as expired CO_2, 7 kg C as feces and urine, and less than 1 kg C as flatus, sweat, and aromatic compounds. In 2000, an estimated 17.2 Tg C were consumed by the US population and 15.2 Tg C were expired to the atmosphere as CO_2. Historically, carbon stock in the US human population has increased between 1790 and 2006 from 0.06 Tg to 5.37 Tg. Displacement and release of total harvested carbon per capita in the US is nearly 12% of per capita fossil fuel emissions. Humans are using, storing, and transporting carbon about the Earth's surface. Inclusion of these carbon dynamics in regional carbon budgets can improve our understanding of carbon sources and sinks.

T. O. West (✉) · G. Marland
Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6335, USA
e-mail: westto@ornl.gov

G. Marland
International Institute for Applied Systems Analysis, 2361 Laxenburg, Austria

N. Singh · B. L. Bhaduri
Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6017, USA

A. B. Roddy
Swarthmore College, Swarthmore, PA 19081, USA

Present Address:
A. B. Roddy
Department of Integrative Biology, University of California-Berkeley, Berkeley, CA 94720, USA

Introduction

Humans are heterotrophic organisms that ingest carbon in the form of complex carbohydrates and release carbon in the form of carbon dioxide,

methane, and a mixture of solid, dissolved, and volatile waste products. As early as 1843 Justus Liebig recognized that humans were heated by the oxidation of carbon compounds and as a result released "carbonic acid" to the atmosphere (Leibig 1843). With a global population now exceeding 6.5 billion people, humans move large amounts of carbon about on the Earth's surface: growing, transporting, and consuming agricultural and forest products. Movement of carbon for human consumption is particularly evident in developed countries where food is now grown in concentrated cropland regions and transported over sometimes large distances for consumption by humans in metropolitan areas and by animals in pasture and rangeland areas and on farms. These transfers of carbon are significant in our attempt to understand the spatial and temporal distribution of the global cycling of carbon (Ciais 2007; Denning et al. 2005). The objective of the current research is to balance the individual, human, metabolic carbon budget and to estimate the spatial and temporal distribution of carbon releases, particularly of carbon dioxide.

Carbon dioxide is taken from the atmosphere by agricultural crops through the process of photosynthesis. After crops are harvested, CO_2 is released back to the atmosphere during the decomposition of crop residues and during the processing and consumption of agricultural commodities by humans and livestock. Released CO_2 is taken up again by crops during the following year or during the next crop rotation. This cyclical process is considered to result in no net emission of CO_2 to the atmosphere (West and Marland 2002a; EPA 2005; Penman et al. 2003). Carbon dioxide is also released to the atmosphere from the use of fossil fuels in agricultural machinery, the production of agricultural inputs such as fertilizers and insecticides, and during the tillage of agricultural soils (West and Marland 2002b); but our focus here is on the photosynthetic products and the ultimate release of the contained carbon.

While uptake and release of carbon may be approximately balanced for the full Earth and at the temporal scale of a year, the uptake and release of carbon can be very much separated in place and over the course of the year. Ciais et al. (2001) analyzed carbon uptake and release by agricultural products, including imports and exports, at a 1×1 degree (latitude/longitude) resolution. Ciais et al. (2001)

concluded that the "horizontal displacement is far from negligible and [that] it has a large impact on the spatial (and temporal) distribution of carbon fluxes over large areas of the world…" In an analysis of global agricultural carbon displacement, Ciais (2007) found that CO_2 emissions in densely populated regions can be 20% higher when considering CO_2 losses from food consumption in addition to fossil-fuel emissions.

In completing a carbon budget for a single US city (Phoenix, Arizona), Koerner and Klopatek (2002) concluded that human activity, including transportation, produced more than 80% of carbon input to the atmosphere. They estimated that 61% of soil CO_2 emissions came from agricultural lands and that human respiration alone contributed as much CO_2 as five power plants. Koerner and Klopatek (2002) noted, as we have above, that respiration from humans is not a net source of CO_2 to the atmosphere, but that humans have a dramatic effect on the carbon balance and the transfer of carbon between regions.

To balance regional carbon budgets it is thus necessary to understand and quantify the location of carbon sources and sinks, and to do this we need to know how humans redistribute carbon around the Earth and in time. The North American Carbon Program is intended to improve estimates of carbon fluxes by improving ground-based and atmospheric-based flux estimates (Denning et al. 2005) and to compare these two estimates for enhanced accuracy (Ogle et al. 2006). The human carbon budget is one component of ground-based estimates.

In this paper, we balance the human carbon budget and estimate the spatial distribution of net carbon release associated with the consumption of agricultural commodities by humans. We focus on the carbon budget, including both CO_2 and CH_4. Net emissions of CO_2 and CH_4 are provided in units of carbon and are also, where appropriate, combined in a standard carbon-equivalent (C_{eq}) unit that is calculated using the 100-year global warming potential of 23 for CH_4 (Ramaswamy et al. 2001). Many components of the human carbon budget have not previously been calculated or documented. We document our calculations for carbon intake, expiration, excretion, other bodily releases of carbon, and the spatial distribution of these releases in the methods section of this paper. Additional details on these calculations are provided in the appendix. We

use the final estimates to conduct an analysis of the US human carbon budget and report the main components of this budget in the results section.

Methods of carbon accounting

Our focus is on the United States. Methods have been developed for estimating carbon uptake by agricultural crops (Hicke et al. 2004; Hicke and Lobell 2004; Lobell et al. 2002; Prince et al. 2001). These methods can be used to estimate carbon uptake at the county level within the US. Release of this carbon occurs in processing plants, in landfills, and during the consumption of food products by humans and livestock. We focus here on the consumption and release of carbon by humans at a sub-county scale. We seek a mass balance for carbon uptake and release by humans and we consider the stock of carbon in humans. For an individual, the intake and output of carbon should approximately balance over the course of a year. We estimate the intake and output independently and compare the two results. Imbalance in the annual carbon budget, in the form of weight gain, is quantified and discussed.

Consumption of carbon by humans

Carbon consumption per capita was estimated by developing carbon coefficients for food commodities and then analyzing food consumption in the US. A list of food commodities and data on food consumption are available in the food commodity intake database (FCID), available from the National Technical Information Service (EPA 2000). The FCID is a compilation of survey data and includes intake of food commodities by age, sex, and race. Survey data collected for the FCID include 2 days of food intake for ∼21,700 individuals, including 11,800 children from birth to 19 years of age. Appendix 1 details the data and assumptions used to arrive at estimates of C intake by humans.

We estimate mean carbon consumption with a 95% confidence interval for all ages at 52.96 ± 0.43 kg C capita^{-1} year^{-1}. Carbon consumption differs significantly between males and females in all age groups with mean male and female intake across all age groups of 60.14 ± 0.70 and 45.56 ± 0.46 kg C capita^{-1} year^{-1}, respectively. Data were analyzed in 5-year age groups commensurate with US population block-group data (US Census Bureau 1994) (see Fig. 7). Age groups that were not significantly different from one another were aggregated into revised age cohorts, and this revised grouping (Fig. 1) was used for the remainder of analyses on the human carbon budget. Average intake for young adults in the 15–39 year age group is 67.33 ± 1.21 kg C year^{-1}. There was no significant difference for carbon intake among different races.

Expiration of carbon by humans

Respiration is the process of inspiring and expiring air. Dry atmospheric air at standard temperature and

Fig. 1 Mean carbon consumption by age and gender in the US. *Brackets* illustrate the 95% confidence interval
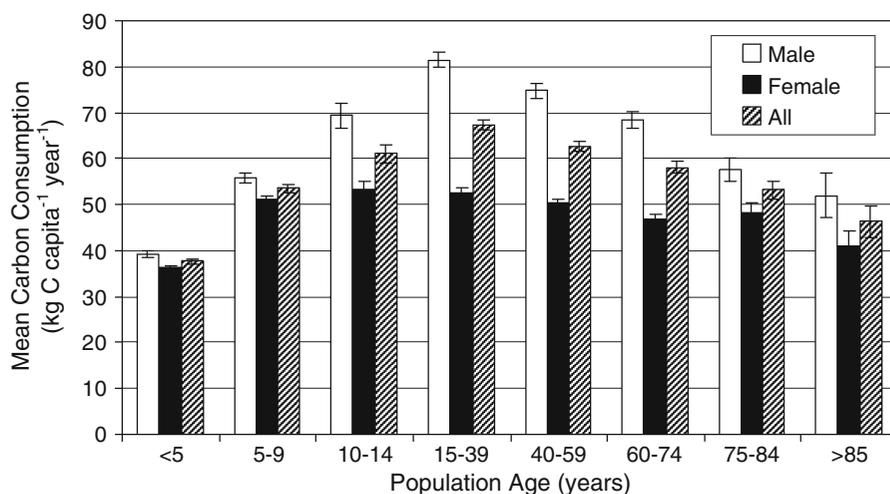
pressure (STP = 0°C and 760 mm Hg) consists of 78.09% (by volume) N_2, 20.95% O_2, 0.03% (now approaching 0.04%) CO_2, 0.93% Ar, and traces of other gases (Weast 1972). The body uses O_2 and generates CO_2, thereby expiring air with about 16.5% O_2 and 3.5% CO_2 (Johnson 1992; Keele et al. 1982; Piiper 1996; Thews 1983; Tuttle and Schottelius 1965). Average minute volume (VE) of air expired is about 6 L, consisting of a tidal volume (VT) of 500 mL per breath at about 12 breaths per minute (Ganong 2001; Johnson 1992; Keele et al. 1982). Mean CO_2 released through human respiration at rest is therefore estimated at about 58.6 kg C year^{-1}. This value represents a healthy young adult, and can increase by an order of magnitude during heavy exercise (Piiper 1996).

Data compiled by Altman et al. (1958) showed a significant difference in ventilation (inspiration and expiration) at rest among age classes and between males and females. These data also showed a significant difference in the percentage CO_2 content of expired air among age classes, but not between males and females. A trend is evident in the efficiency of oxygen use and CO_2 generation with increasing age, such that air intake increases while the percentage of CO_2 in expired air decreases (Fig. 2). Combining volume of expiration with the concentration of expired CO_2 indicates a trend of total expired CO_2 over a gradient of age (Fig. 3) similar to that of food consumption (see Fig. 1). This trend supports our assumption of approximately equal

carbon inputs and outputs for the annual human carbon budget.

Excretion and secretion of carbon by humans

In addition to expiring CO_2 during the process of respiration, humans also release carbon as excreta, flatus, sweat, and aromatic compounds. Humans excrete, on average, 80–170 g feces and 1,000 g urine per capita per day (Orten and Neuhaus 1982). Carbon in flatus and sweat is a relatively small component of the human carbon budget, but is included here for completeness. Appendix 2 details our estimates of carbon excretion and secretion by humans. Our estimates are that average per capita loss of carbon by humans in the US is 4.62 kg C year^{-1} in feces, 1.93 kg C year^{-1} in urine, 0.0815 kg C year^{-1} in sweat, and 0.0293 kg C year^{-1} (0.1154 kg C_{eq} - year^{-1}) in flatus.

The treatment of solid or liquid wastes following their exit from the body influences whether the carbon is emitted to the atmosphere as CO_2 or CH_4. About 25% of domestic wastewater in the US is treated in septic systems (EPA 2005). The remainder of domestic wastewater is treated in central wastewater treatment facilities where the waste is decomposed by either aerobic or anaerobic processes. It has been estimated that 16.25% of wastewater is anaerobically digested (EPA 2005), and this estimate includes treatment in septic systems. As detailed in Appendix 2, our estimate is that total annual carbon release from human waste is

Fig. 2 Volume of expired air versus carbon content of expired air in 32 subjects ranging from 9 to 85 years of age. Data compiled by Altman et al. (1958)
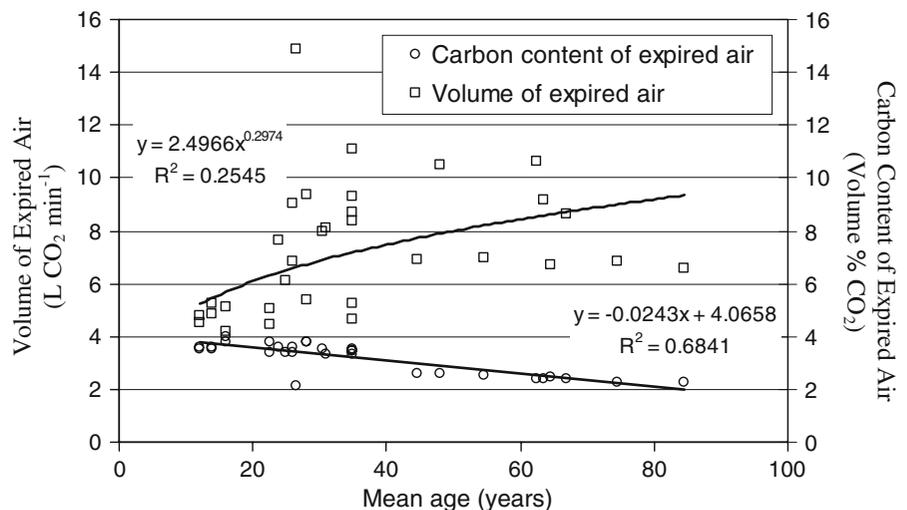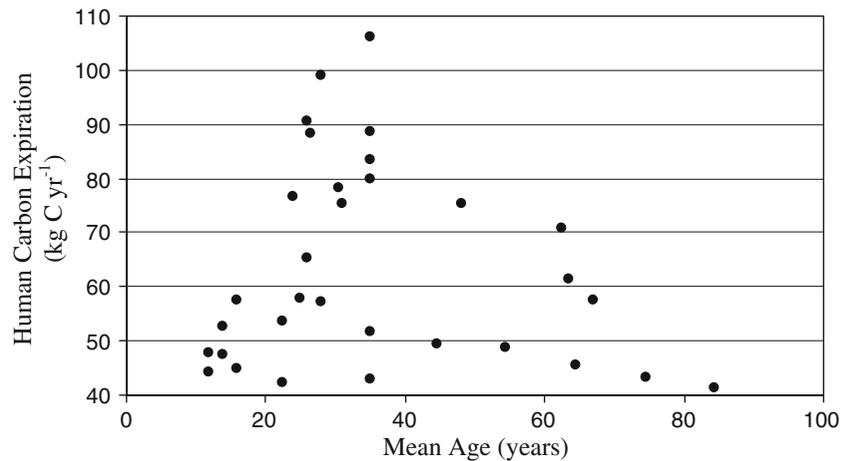
Fig. 3 Total carbon expiration for 32 subjects, ranging from 9 to 85 years of age. Total expired carbon is the multiple of the volume of expired air and the fractional carbon content (see Fig. 2). Data compiled by Altman et al. (1958)

0.53 kg C capita^{-1} year^{-1} as CH$_4$ and 6.02 kg C capita^{-1} year^{-1} as CO$_2$, with another 0.11 kg C capita^{-1} year^{-1} as volatile and inorganic compounds in flatus and perspiration. Considering the global warming potential of CH$_4$, total net C$_{eq}$ emissions from human waste and subsequent waste treatment is 10.65 kg C$_{eq}$ capita^{-1} year^{-1}.

Our analysis of the fate of CO$_2$ from human waste assumes that emissions occur in the same year that carbon is excreted from the body. The majority (75%) of human waste in the United States is processed at wastewater treatment plants, and these treatment plants increase the rate of decomposition in an effort to reduce the chemical oxygen demand of waste effluent. Remaining solid waste is dried and transported to hazardous waste landfills (Jack Graham, Engineer and Assistant Director of Water Quality, Maryville, TN, USA). Emissions of N$_2$O also occur from processing the nitrogenous compounds in human waste at wastewater treatment facilities (Czepiel et al. 1995). In conducting an analysis of N$_2$O emissions from a wastewater treatment plant in Durham, New Hampshire, Czepiel et al. (1995) estimated net per capita N$_2$O emissions of 0.0032 kg N$_2$O per year. The focus here is on the human carbon balance and these compounds are not considered further in spite of the fact that N$_2$O is a greenhouse gas.

Carbon stock of humans

The uptake and loss of carbon by humans represent carbon flows. The total human population is a carbon stock, and this stock changes over time as the total US population increases in number and in mass per person. The human body consists of about 60% water, 15% protein, 6% minerals, and 19% fat (ICRP 1975; Going 1996). Almost all carbon in the body is found in fat, protein, and glycogen, with smaller amounts of carbon in bone mineral and lipids (Heymsfield et al. 1996). As detailed in Appendix 3, our estimate of carbon content in the average human adult is 20.7 kg C per capita. Average carbon content across all ages, ranging from 8 to 27 kg C per capita, is 17.3 kg C per capita.

The historical change in human carbon stock in the US is nearly proportional to the increase in population, with the addition of historical changes in average body mass. Average mass and height among adults increased 11 kg and 2.5 cm, respectively, between 1960 and 2002 (Ogden et al. 2004). Increase in the body mass index (BMI—a measure of mass in kilograms divided by height in meters) indicates that fat gain, not height increase, was the main contributor to the increase in average mass (Ogden et al. 2004). Weight gain and obesity are an increasing concern in the US and Blanck et al. (2006) report that obesity in the US has increased from 15.3% in 1995 to 23.9% in 2005. The mass estimates in this analysis are based on sample data from the FCID (EPA 2000), which were taken between 1994 and 1996. We corrected for changes in average mass across age categories since 1960, based on data presented by Ogden et al. (2004). Between 1790 and 2006, the US population increased nearly 80-fold from 3.9 million to 300 million (Fig. 4). In this same time period, the human carbon stock increased from 0.06 Tg to 5.37 Tg (teragram = million metric tonne), with half of this increase occurring since 1950. Had there not been the ∼5% increase in average per capita

Fig. 4 Carbon stock in the US human population from 1790 to 2000. This historical trend is based on census population data (US Census Bureau 1993, 2002) and an average 17.3 kg C per capita. The last point on the graph represents the estimated US population of 300 million on October 17, 2006
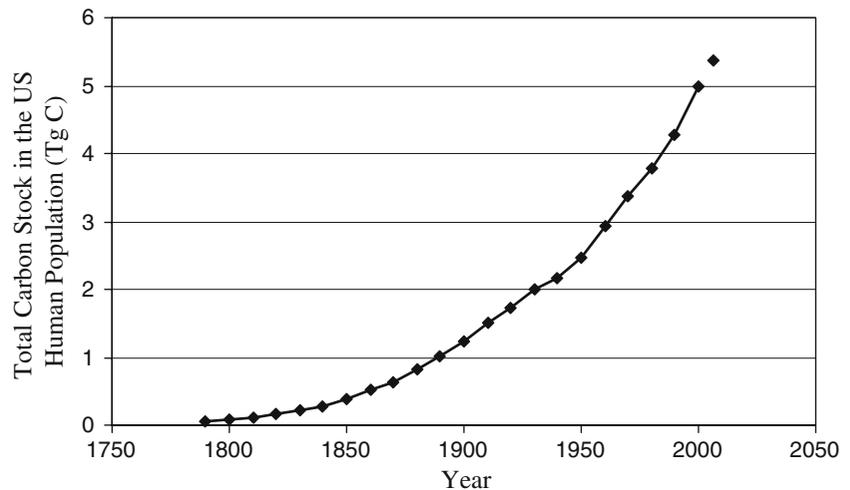
weight between 1990 and 2000, with an additional 2% increase projected to 2006, the US human population would instead have been sequestering 4.84 Tg C in 2006.

Geospatial distribution of human respiration

To estimate the release of carbon by humans we need to first estimate how the human population is spatially distributed. LandScan (Dobson et al. 2000, Bhaduri et al. 2007) is a grid-based population dataset that estimates where people are located around the world at a resolution of 30 arcseconds ($\sim$1 km $\times$ 1 km at the equator). LandScan combines data on population, road networks, digital terrain, schools, prisons, commercial and residential buildings, and nighttime lights with high-resolution satellite imagery to estimate where people are located during the day and during the evening. In our analysis, we use a US version of LandScan for year 2000 that uses block-group population data from the US Census Bureau and that estimates the ambient (i.e., integrated diurnal movements) location of humans at a resolution of 15 arcseconds ($\sim$450 m $\times$ 450 m). Estimates of carbon intake and release by humans are applied to unique age and sex categories within the block-group demographic data and then distributed within the LandScan model. The model does not distinguish variations that might occur over the course of a year so it does not capture any differences in respiration that might occur due to an annual variation in the level of human activity or of human distribution. Our computation distinguishes between human respiration and the discharge

of other waste products but this cannot be captured by LandScan so the assumption is implicit that all of these emissions occur in the same place. LandScan allows for estimates, at the finest scale possible, of the direct release of human carbon into the atmosphere, the approximate location of net C_{eq} flux from humans (including the treatment of human waste), and the stocks of human carbon in the US.

Results and synthesis

The average adult (ages 15–39) in the US contains about 20.7 kg C. Our best estimate of the carbon budget for an average person in the US achieves reasonable balance between annual carbon intake and annual carbon output (Fig. 5). Our estimate is that the average young adult, between the ages of 15 and 39, takes in about 67.0 kg C year^{-1}, and that this is balanced by release of about 65.5–58.6 kg C as expired CO_2, 6.6 kg C as feces and urine, and considerably less than 1 kg C as flatus, sweat, and aromatic compounds (Fig. 5). Carbon that is excreted in the US is treated in private septic systems or municipal wastewater treatment facilities with the combination of these two processing methods releasing about 6.02 kg C as CO_2, 0.53 kg C as CH_4, and 0.11 kg C as other volatile and inorganic species. In our analysis, we associate emissions from waste with the same year in which they were excreted from the body.

Balancing the carbon budget for the average human adult involves estimates of total carbon consumption and of the fractional loss of carbon by
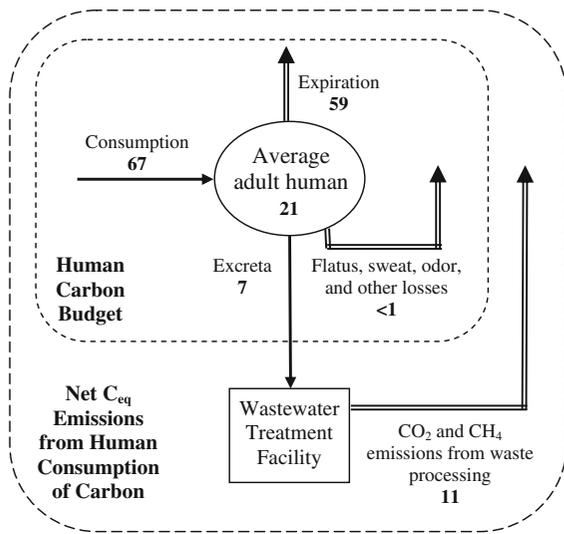
Fig. 5 Schematic of consumption, metabolization, and post-waste processing of consumed carbon in the US. *Solid lines* represent transfer of solid carbon and *double lines* represent loss of gaseous carbon emissions. Excreta includes feces (5 kg C) and urine (2 kg C). Units are kg C per year for an average adult (ages 15–39), except for units of net C_{eq} emissions from wasterwater treatment facilities that includes a global warming potential (GWP) factor of 23 for CH_4

different physiologic pathways. Given estimates of carbon consumption for different age-gender categories, the fractions of carbon loss for an average adult can be applied to individual age–gender categories (Table 1). Since the carbon budget is required to be balanced for each age–gender category, carbon consumed will equal the sum of carbon expired and the carbon excreted for each category. Total release of greenhouse gases is the sum of carbon expired and carbon released from the treatment of excreted carbon. The carbon stock per capita uses a model for total body carbon along with an estimated percentage of body fat for each age–gender category. Carbon consumption data are based on a survey of the US population; therefore, our estimates of human carbon stocks and flows represent the US population.

We are able to estimate total human stocks and flows of carbon in the United States by combining our estimates of carbon stocks and flows for different age–gender categories with population data from LandScan (Fig. 6). In 2000, an estimated 17.2 Tg C were consumed by the US population and 15.2 Tg C were expired to the atmosphere as CO_2. Including

Table 1 Estimated carbon consumed, released, and stored by the US population

Age (gender)	Carbon consumed (kg C capita^{-1} year^{-1})	Carbon expired	Carbon excreted[a]	Total release of CO_2 and CH_4 (kg C$_{eq}$ capita^{-1} year^{-1}[b])	Estimated carbon stock (kg C capita^{-1})
<5 (M)	39.3	34.6	4.7	41.0	8.1
<5 (F)	36.2	31.9	4.3	37.8	8.1
5–9 (M)	55.8	49.1	6.7	58.3	9.2
5–9 (F)	51.0	44.9	6.1	53.2	9.2
10–14 (M)	69.3	61.0	8.3	72.3	12.0
10–14 (F)	53.4	47.0	6.4	55.7	12.1
15–39 (M)	81.4	71.6	9.8	85.0	18.0
15–39 (F)	52.6	46.3	6.3	54.9	22.6
40–59 (M)	74.8	65.8	9.0	78.1	21.1
40–59 (F)	50.3	44.3	6.0	52.5	25.5
60–74 (M)	68.3	60.1	8.2	71.3	20.6
60–74 (F)	46.8	41.2	5.6	48.9	27.2
75–84(M)	57.7	50.8	6.9	60.2	21.6
75–84(F)	48.2	42.4	5.8	50.3	24.1
>85(M)	51.9	45.7	6.2	54.2	18.8
>85(F)	41.1	36.2	4.9	42.9	18.9

[a] Excreted carbon includes feces, urine, flatus, and secretion of sweat and odor

[b] Carbon-equivalent (C_{eq}) emissions include carbon expired and the CO_2 and CH_4 emissions from excreted carbon that is decomposed at wastewater treatment facilities and municipal solid waste facilities, using global warming potential values of 1 and 23 for both gases, respectively
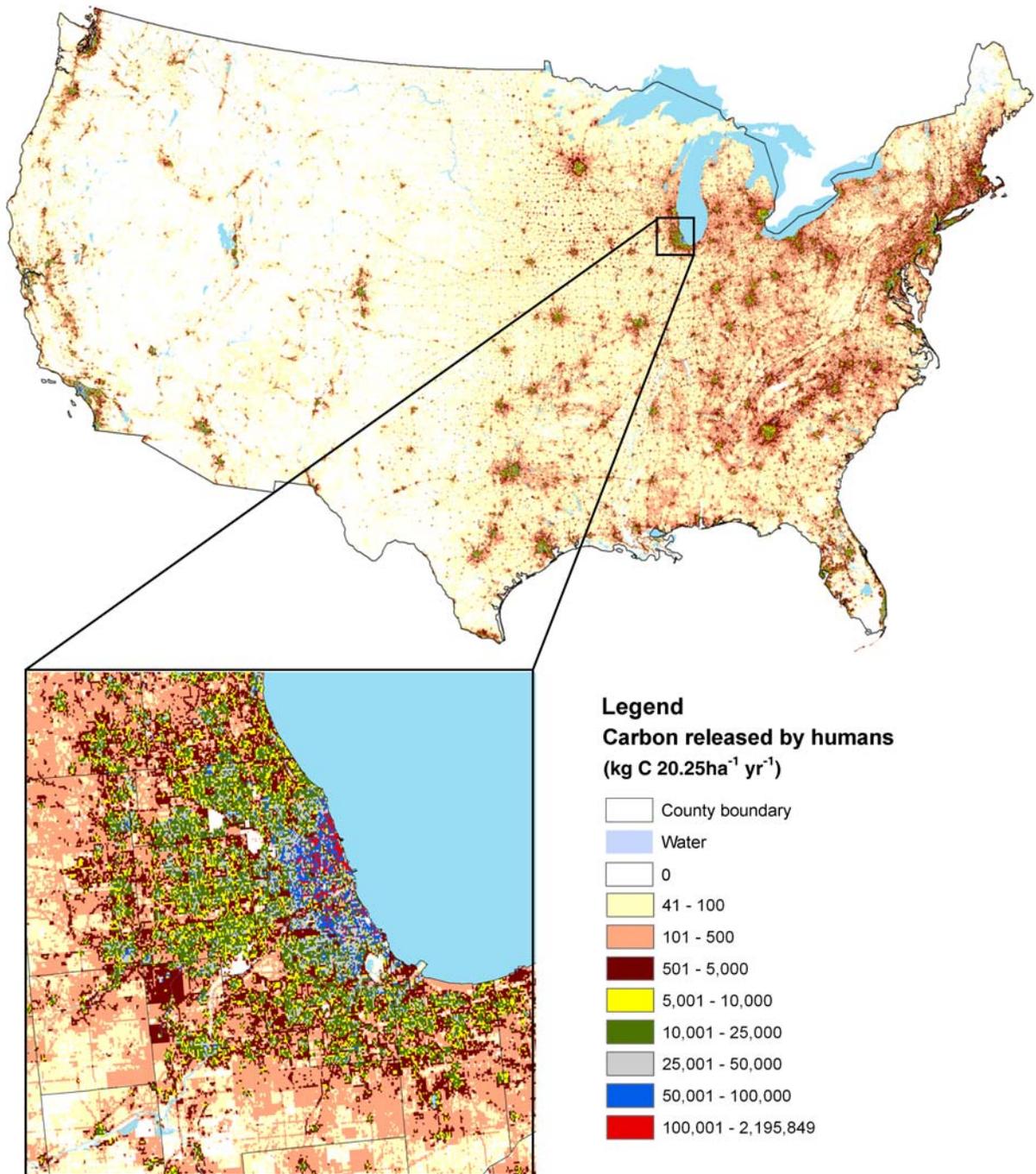
Fig. 6 Carbon released directly by the US human population in 2000. Enhanced area represents carbon released in the metropolitan area of Chicago, Illinois, USA. Spatial resolution is commensurate with the 450 m × 450 m (20.25 ha) Landscan 2000 data

excretion and secretion of carbon, it is expected that the entire 17.2 Tg C was released to the atmosphere the same year. Increases in population and personal body mass result in some small annual increase in

carbon stocks. The spatial distribution of carbon release by humans is nearly opposite the distribution of carbon uptake by agricultural crops (see Hicke et al. 2004).

Figure 6 shows that the densely populated areas of the United States are strong sources of CO_2 from human respiration. With average per capita consumption of agricultural carbon at 67 kg C year^{-1} and average per capita use of fossil-fuel carbon at 5430 kg C year^{-1} (Marland et al. 2006), emissions from human respiration are 1.2% of those from fossil-fuel use when averaged over the country. The fraction is likely to be somewhat larger in densely populated areas. The fraction is likely to be still larger in urban concentrations of developing countries where there is less automobile traffic. Our estimate includes only the agricultural carbon that humans directly consume and subsequently respire. If we consider total harvested carbon in the US (Ciais et al. 2007) divided by total US population, as is done with the estimate for fossil-fuel consumption per capita, we then compare agricultural carbon use of 627 kg C year^{-1} with fossil-fuel use of 5430 kg C year^{-1} and see that the displacement and release of total harvested carbon is nearly 12% of fossil-fuel emissions. Tracking carbon flows in all agricultural commodities would include consumption and use by humans and livestock, processing wastes, textile products, and imports and exports. We have documented the human component of agricultural carbon displacement here.

Appendix 1: Consumption of carbon by humans

Carbon coefficients were calculated for 549 food commodities in the food commodity intake database (FCID) by adjusting production values to dry weight and multiplying by the mass fraction of carbon. Moisture content of harvested foods is highly variable. The fraction that is dry weight of fruits and vegetables is ~ 0.2, with fleshy fruits and melons being closer to 0.1. In generating our carbon coefficients, fruits, vegetables, and tubers were taken to have a dry weight fraction of 0.2; nuts and seeds were taken at 0.9; and oils at 1.0. Baby foods were assumed to have a dry weight fraction of 0.1, because of the water added to make the product suitable for consumption by infants. Harvested grains are between 0.7 and 0.9, with corn grain at 0.87. Fractional carbon content of agricultural crops is about 0.40 of dry weight (Brady and Weil 1996).

Carbon coefficients were joined to the FCID food commodities so that commodity consumption, along with its carbon content, could be queried for different demographic categories. Food commodity data were analyzed to estimate mean carbon consumption by age, gender, and race in a manner that coincides with population block-group data reported by the US Census Bureau (1994). Results are presented as mean carbon consumption per capita, with associated 95% confidence intervals (Fig. 7).

Carbon consumption peaks in the 20–24 age range for males (82.68 ± 4.64 kg C capita^{-1} year^{-1}) and in the 25–29 age range for females (54.67 ± 2.99 kg C capita^{-1} year^{-1}). However, peak consumption for these age groups is not significantly ($\alpha = 0.05$) different from adjacent age groups (Fig. 7). We aggregated age groups that are not significantly different, resulting in revised age categories that are significantly different from each other (see Fig. 1). For the male age groups, all revised age groups (see Fig. 1) are significantly different from adjacent classes with the exception of age groups 75–84 and >85. In these last two age groups, there is a significant difference for females. Age classes used for the remainder of analyses in this paper are as shown in Fig. 1.

Appendix 2: Excretion and secretion of carbon by humans

Human feces composition is 75–80% water and 20–25% solids (Waldeck 1983), with C representing about 40–50% of solids. Taking the midpoint of all aforementioned ranges, we estimate about 4.62 kg C per capita year^{-1} in feces, based on a per

Fig. 7 Mean carbon consumption by age and gender in the US. *Brackets* illustrate the 95% confidence interval
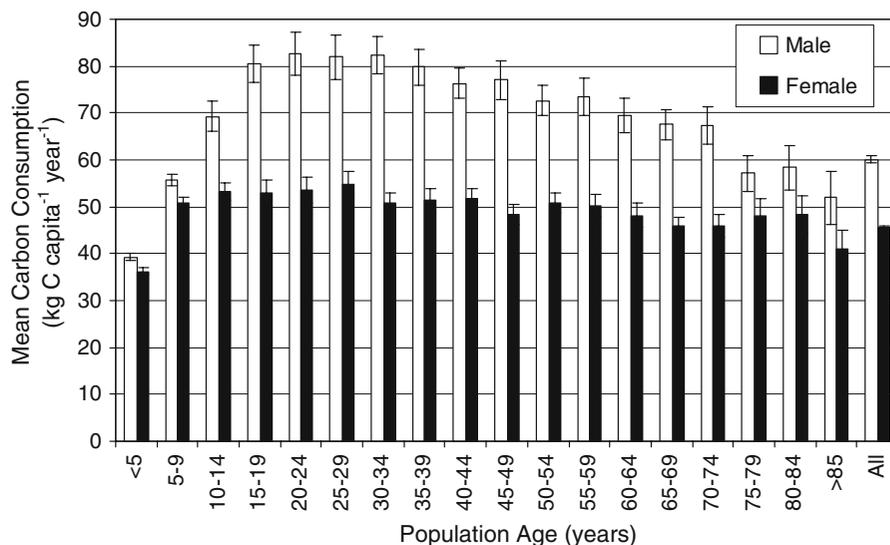
capita daily average of 125 g feces consisting of 22.5% solids and 45% carbon. Daily per capita excretion of urine is 1.0–1.5 L in the northern US, but less in the south and on summer days ($\sim$600 mL) because of increased diversion of water to the skin and lungs (Orten and Neuhaus 1982). Urea ($CO(NH_2)_2$) is the principal constituent in urine and is excreted at 18–35 g per day, or 26.5 g per day on average (Orten and Neuhaus 1982; Keele et al. 1982). Using a simple mass balance approach to estimate carbon content of urea results in 1.93 kg C per capita year^{-1}.

Carbon in flatus and sweat is a relatively small component of the human carbon budget, but is included here for completeness. Gas is produced in the human gastrointestinal tract as consumed food is metabolized. The average volume of gas in the gastrointestinal tract is 200 mL and daily production is 500–1,500 mL (Ganong 2001). A weighted average of flatus composition from three separate experiments, consisting of 31 individuals on regular diets (Levitt et al. 1981), revealed fractions of elemental gas in collected flatus to be 9.0% CO_2, 6.0% CH_4, 17.7% H_2, 3.3% O_2, and 63.9% N_2. Assuming daily average flatus of 1 L at STP, we estimate annual per capita emissions of 64.5 g CO_2 and 15.6 g CH_4 or a total carbon release of 29.3 g C. Considering the global warming potential of CH_4 brings this total to 115.4 g C_{eq} per capita year^{-1}.

Secretion of human sweat occurs primarily to evaporate water which cools the body and prevents overheating. Sweat is a water-based fluid containing Na^+, Cl^-, K^+, HCO_3^-, Ca^{2+}, Mg^{2+}, urea, nitrogenous compounds, lactic acid, small amounts of glucose, and iron (Cooper 1996; Greger 1996). Water evaporates from the skin at an approximate rate of 600 mL per day (Guyton 1981). This rate does not reflect thermoregulation or increased rates of sweating related to physical exercise or nervousness. Rates of sweating following exercise can reach 1.5 L h^{-1}, and maximum rates of sweating in humans are as high as 2–4 L h^{-1} (Greger 1996). If we assume the HCO_3^- concentration in sweat to be 31 mmol L^{-1} with 600 mL of sweat per day, average loss of carbon through sweat secretion would be about 81.5 g C per capita per year. Sweat also includes trace amounts of carboxylic acids, including 3-methylbutanoic acid (isovaleric acid), that are responsible for the sweat-like smell (Schild 1996). The concentrations of these acids in sweat are small (Constantini et al. 2001) and their contribution to the human carbon balance is ignored here.

The concentration of organic compounds in wastewater treatment facilities is measured in units of biological oxygen demand or chemical oxygen demand (COD). We use units of COD in this analysis. Total organic carbon (TOC) in wastewater is a measure of all organic carbon substances in the water column. The chemical oxygen demand (COD) is a measure of the amount of oxygen used during the oxidation of TOC to carbon dioxide. The COD/TOC correlation factor is estimated from the theoretical

ratio of molecular weight of oxygen divided by that of carbon. The maximum methane producing capacity of domestic wastewater is 0.25 kg CH_4/kg COD (Penman et al. 2000). Using our previous estimate of 6.55 kg C excreted (4.62 as feces, 1.93 as urine), and a COD/TOC ratio of 2.67, we estimate that anaerobic digestion of human waste produces about 0.71 kg CH_4 per capita per year. Since CH_4-producing organisms generate equal amounts, by volume, of CH_4 and CO_2 (see EPA 2002), we estimate CO_2 emissions of 1.95 kg CO_2 per capita per yr associated with anaerobic digestion. This estimate is based on the mass balance of CH_4 and CO_2. The remaining 83.75% of domestic wastewater is assumed to be treated aerobically with carbon released as CO_2. Total carbon release from human waste is thus 0.53 kg C per capita as CH_4 and 6.02 kg C per capita year^{-1} as CO_2, with another 0.11 kg C per capita year^{-1} as volatile and inorganic compounds in flatus and perspiration.

Appendix 3: Carbon stock of humans

Fat mass at birth is about 14% of body mass and this fraction increases within the first year to about 26%. Increased fat mass is maintained through the first few years of growth. By age five, the percentage of fat mass has decreased to about 15% of body mass, with girls having about 14% more fat than boys (Van Loan 1996). In young adults (ages 20–39) average fat mass is about 19% for men and 32% for women, and this typically increases in older adults (ages 40–90) to about 23% for men and 35% for women (Watson et al. 1980; Lohman 1996). This same trend was shown by the ICRP (1975) based on a compilation of multiple studies on newborns, adolescents, and adults. Watson et al. (1980) provided average mean body fat for 458 male subjects and 265 female subjects by 10-year age increments, from ages 20 to 90, and we use these average values in our analysis.

Using the aforementioned estimates of fat mass and using data on average body mass queried from the FCID data (EPA 2000) for the age and gender classes in Fig. 1, we can estimate average fat mass across age and gender. A total body carbon (TBC) model (Kehayias et al. 1991) can be used to estimate TBC based on fat mass and other predefined variables (Heymsfield et al. 1996). The foundation of the TBC model is that carbon constitutes 77% of fat mass, 53.2% of protein mass, and 44.4% of glycogen mass. Protein carbon can be estimated using a total body nitrogen/protein ratio of 0.16 with average total body nitrogen of 1800 g N per body, and glycogen can be estimated using a glycogen/protein ratio of about 0.044 (Heymsfield et al. 1996). Using an average body mass of 72.69 kg for both males and females of age 15–39, and a percent fat mass of 25.8%, we estimate the carbon content in the average human adult at 20.6 kg C. This total carbon content consists of 14.4 kg C in fat, 6.0 kg C in protein, and 0.2 kg C in glycogen.

Changes in carbon stocks due to births and deaths are inherently included in the carbon stock estimate associated with the current population. However, releases of CO_2 are associated with cremation and there is additional, short-term carbon stocks associated with buried cadavers. Cremation in the US increased from about 3% in the mid 1930s to 30% in 2004 (CANA 2007). In 2000, 629,362 cadavers or 26.2% of the deceased US population were cremated. Mitchell et al. (1945) reported that 85.7% of human ash content is from the skeleton and teeth, with only 0.51% from adipose tissue. Since only a very small fraction of body carbon is found in bone (Heymsfield et al. 1996), the majority is incinerated during cremation. Using the previously calculated estimate of 17.3 kg C per capita, we estimate 10,888 Mg C emitted in 2000 from the cremation of human cadavers.

The remaining deceased population not cremated each year is buried, many of whom are embalmed prior to burial. Complete decomposition can take place over a wide range of time, depending on the type and dilution of embalming fluid, the method of embalming, and the ambient temperature and moisture of the burial site. We assume for this analysis that the majority of the body is decomposed after a decade and this decomposition results in the oxidation of carbon compounds (Strub and Frederick 1967). Emissions of CO_2, regardless of the container used for burial, will be transferred to the surrounding soil environment and then exchanged with the surrounding atmosphere.

The percent of cadavers cremated each year increases along with increasing population in the short term, such that the number of cadavers buried in the US has remained fairly constant from 1963 to

2004 at between 1.7 and 1.8 million year^{-1}. If the number of cadavers buried remains relatively stable each year, as does the average rate of decomposition, emissions from decomposition will remain fairly constant at about 30,275 Mg C year^{-1}. Likewise, the carbon stock of humans buried each year will be relatively constant at 30,275 Mg C year^{-1}.

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