# Accounting for global carbon dioxide production from human metabolism between 1985 and 2015: a modelling study

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## Summary

**Background** Human activity is a dominant driver of global carbon emissions, yet one universal source–human metabolism–has never been quantified using free-living measurements of carbon dioxide ($CO_2$) production at scale. We aimed to describe the contribution of human metabolism to global $CO_2$ emissions between 1985 and 2015.

**Methods** In this modelling study, we used the largest available database of doubly labelled water (DLW) measurements from 1986 to 2019. The other data sources comprised WHO Global Health Observatory, United Nations Department of Economic and Social Affairs, and Non-communicable Disease Risk Factor Collaboration. We first allometrically modelled human $CO_2$ production (kg per year) using measurements available for 4479 female and 2277 male participants from the International Atomic Energy Agency DLW database to derive predicted estimates of human $CO_2$ production adjusted for differences in body mass and sex. Second, by combining predicted estimates based on allometric scaling of $CO_2$ production for body mass with available population demographic information, generalised additive models were used to describe the 30-year progression of human body mass and per capita and global $CO_2$ production. We used the time-series country-specific measurements from 1985 to 2015 with population-level global human metabolic $CO_2$ production summarised as cumulative sum for the progression analyses.

**Findings** Data were collected between 1986 and 2019. Mean ± SD (range) participant age was 40 ± 26 (0 to 101) and body mass was 63.3 ± 27.8 (2.4 to 101.9). 9006 measurements from 6756 participants (4479 women and 2277 men) from the DLW database were used to derive estimates of human $CO_2$ production adjusted for differences in body mass and sex. We observed that human metabolic $CO_2$ production approximately doubled over a 30-year period, from 1·18 Gt per year to 2·05 Gt per year. This increase was driven mostly by population growth (>60%) with a minor contribution from increases in body mass. Per capita sex differences equalised at the population level, and continental differences reflect population shifts rather than physiological differences, with Asia accounting for the majority of human metabolic $CO_2$ production among all continents.

**Interpretation** Our findings suggest that human metabolism is a quantitatively important component of the fast carbon cycle and should be accounted for in carbon system modelling to enhance precision and fidelity. With a projected peak global population in the mid-to-late 21st century, metabolic $CO_2$ production will increasingly contribute to global carbon fluxes.

**Funding** The the DLW database was funded by The International Atomic Energy Agency, Taiyo Nippon Sanso, and SERCON.

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*Lancet Planet Health* 2026

Published Online
https://doi.org/10.1016/j.lanplh.2026.101546

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## Introduction

The success of humans as a species has resulted in substantial population growth. This growth has indirectly increased carbon dioxide ($CO_2$) emissions from fossil fuels and land-use change associated with human activity.[1] These sources are considered anthropogenic because they introduce previously sequestered carbon into the atmosphere. However, population growth also affects $CO_2$ flux via human metabolism—a biogenic process that has not been estimated using $CO_2$ models across the full range of human ages and masses at a global scale.

The full integration of human dynamics in biophysical systems, which includes human metabolic $CO_2$ production, is a key challenge in Earth system science.[2] Human metabolic $CO_2$ production is an inevitable consequence of cellular respiration, through which food-derived carbon is oxidised and returned to the atmosphere.[3] Cellular respiration is part of the fast carbon cycle; that is, it generally does not add new carbon to the atmosphere but recycles carbon that was recently fixed by plants. Nevertheless, a rapidly growing human population, with the need to use more resources to fuel metabolism, can jeopardise the fast carbon cycle by contributing to total $CO_2$ release and potentially exceed Earth's capacity to recapture and store carbon, decoupling the fast cycle. Accordingly, human metabolic $CO_2$ represents a key point in carbon flow

## Research in context

### Evidence before this study

We searched PubMed, Web of Science, and Google Scholar for studies from the date of inception up to March 28, 2026, using terms including "human metabolism $CO_2$", "metabolic carbon dioxide production", "biogenic carbon flux humans", "doubly labelled water $CO_2$", and "human carbon budget". We also screened the reference lists of relevant reviews and Earth system science reports. We included studies that attempted to quantify human metabolic $CO_2$ production or incorporated human respiration into carbon cycling models. We prioritised the studies that involved empirical measurements and studies with only theoretical assumptions were completely excluded. Although some estimates of human metabolic $CO_2$ production were previously provided, these were typically derived indirectly from carbon intake calculations or from laboratory-based indirect calorimetry studies in small samples (often <30 participants) of average young adults and thus do not capture real-world variation or population heterogeneity.

### Added value of this study

To the best of our knowledge, this study provides the first global description of human metabolic $CO_2$ production based on a model derived using measurements from the International Atomic Energy Agency doubly labelled water database, encompassing the data from thousands of individuals across different ages, body sizes, and geographical regions. By combining these data with population, anthropometric, and dietary datasets, we modelled the changes in global metabolic $CO_2$ production from 1985 to 2015. We show that global human metabolic $CO_2$ production nearly doubled over this period, increasing from approximately 1·8 to 2·05 $GtCO_2$ per year, with more than 60% of this rise driven by population growth and smaller contributions from increased body mass.

### Implications of all the available evidence

Human metabolic $CO_2$ production is an important component of carbon cycling and should be incorporated in climate models for optimal understanding of carbon flux. Although metabolic $CO_2$ is biogenic and part of the short-term carbon cycle (ie, not contributing net carbon to the atmosphere), its magnitude and sensitivity to population dynamics indicate that it can influence total carbon fluxes and the interpretation of mitigation strategies.

through human food systems. Despite the biogenic nature of human metabolism, the accurate modelling and prediction of global carbon fluxes require an understanding of human metabolic $CO_2$ in addition to anthropogenic sources of $CO_2$.[4,5] Misestimation or exclusion of human biogenic carbon flux can affect predictive modelling and effectiveness of policy interventions aimed at anthropogenic $CO_2$ emissions. Notably, flux of biogenic cycles can either accelerate or slow the rate of greenhouse gas accumulation, thereby modulating the pace of local or global climate change.[5,6] Global $CO_2$ resulting from human metabolism has not been formally quantified using doubly labelled water (DLW) measures of $CO_2$ during carbon flux model development, and, therefore, estimating the full effect of human population growth or of the spread of obesity or changes in physical activity levels on $CO_2$ flux has not been possible.

If human metabolic $CO_2$ production is substantial, it could have important implications for modelling the effects of policies and interventions on the carbon cycle. For example, the apparent effects of diets with low carbon footprints associated with food production and transport could differentially alter $CO_2$ flux if they substantially increase human metabolic $CO_2$ production.[7] Theoretically, this increase could occur with plant-based diets, such as the EAT-*Lancet* Commission's Planetary Health Diet; the Planetary Health Diet tends to have a low carbon footprint up until the point of human consumption[8,9] but also tends to have a high food quotient (ratio of $CO_2$ production to oxygen consumption upon oxidation of the diet) because of the higher carbohydrate-to-fat ratio.[9,10] During energy balance, the respiratory quotient equals the food quotient,[11] and thus human metabolic $CO_2$ production can increase more from diets with a high food quotient than from those with a low food quotient. Further, strategies aimed at reducing obesity or increasing physical activity would also have implications for $CO_2$ modelling, in addition to direct effects on human health. All other factors being equal, reductions in prevalence of obesity would reduce human metabolic $CO_2$ production (and flux), whereas common public health recommendations promoting increases in physical activity would increase human metabolic $CO_2$ production. Therefore, accurate quantification of human metabolic $CO_2$ production and its determinants are required to know whether carbon modelling should account for human metabolism.

The International Atomic Energy Agency (IAEA) DLW database provides a unique opportunity to describe global human metabolic $CO_2$ production.[12] DLW can provide an accurate and reliable measure of average $CO_2$ production by a human during free-living conditions over a period of approximately 2 weeks,[13] as the differences in the elimination rates of labelled hydrogen ($^2H_2O$) and oxygen ($H_2{}^{18}O$) are directly proportional to $CO_2$ production rates.[13,14] The IAEA DLW database has data from over 7000 people across 45 countries, with ages ranging from newborns to over 100 years and body mass ranging from 2 kg to almost 200 kg. Indirect estimates of human metabolic $CO_2$ have been made from deduction-based methods using estimated carbon intake and average ratios of exhaled $CO_2$

relative to carbon intake for healthy young adults[15,16] and from laboratory-based indirect calorimetry; such calorimetric techniques were used to extrapolate measured $CO_2$ emissions from breath samples within laboratory conditions in small numbers of participants (typically n<30).[15,17–20] However, as there is large interindividual and intraindividual variability in human metabolic $CO_2$ production,[17,21] large sample sizes and adequate observation periods under free-living conditions are required to derive robust estimates of $CO_2$ production for a wider population.

Our study aimed to model human metabolic $CO_2$ production and describe the global $CO_2$ contribution from humans over a 30-year period from 1985 to 2015 using the data from IAEA DLW database and the UN database of population demographics.[12,22,23] The selected timescale of 1985–2015 represents a period of increased global human population size and body mass, for which we have the data required for global modelling. We also aimed to describe the contributions to global $CO_2$ emissions from the metabolism of men and women, and across age ranges and continents.

## Methods

### Study design and data source

In this modelling study, we modelled human $CO_2$ production (kg per year) using the data from the IAEA DLW database, covering thousands of individuals across all ages (<1 to >100 years), body sizes (2·4 to 192·4 kg body mass) and continents, to derive predicted estimates of human $CO_2$ production adjusted for differences in body mass and sex. The details of the database have been described elsewhere,[12] and the information is available on the IAEA website. We used the database version 3.7, which excluded data from amateur and professional athletes because their high levels of physical activity result in substantially elevated $CO_2$ production rates that are not representative of the general population. We included participants with complete data on sex, body mass, location, and $CO_2$ production rate. Data were collected between 1986 and 2019. Details of the eligibility criteria cannot be provided because the DLW database comprises more than 100 individual studies, each with its own eligibility criteria. Sex and ethnicity were collected by self-report (appendix 1 pp 3).

This project received favourable ethical opinion from the Biomedical Sciences Research Ethics Committee at the University of Bath (reference no. 11927–13804).

### Procedure

We adopted an information-theoretical approach and used the Akaike Information Criterion to compare three sets of four candidate models assuming multiplicative, log normal, and heteroscedastic error; additive, normal, homoscedastic error; additive, normal, heteroscedastic error;[24] and a conventional two-parameter power function with log-normal heteroscedastic error of the form $Y=a\cdot X^b$. The model fitted with the two-parameter power function for scaling $CO_2$ production as a biological component for differences in body mass informed the second step.

By combining predicted estimates based on the allometric scaling of $CO_2$ for body mass with available population demographic information,[22,23,25] generalised additive models were used to describe the 30-year progression of human body mass and the expected per capita and global $CO_2$ production using time-series country-specific measurements from 1985 to 2015, the period for which data were available across all data sources with population-level global human metabolic $CO_2$ production summarised as the cumulative sum (appendix 1 pp 3–8, appendix 2 table S3, table S4, and table S5).[26]

See Online for appendix 2

### Statistical analysis

Allometric scaling analyses were conducted using the MODEL procedure available in SAS OnDemand for Academics. We conducted non-linear regression analyses of untransformed measurements to normalise human $CO_2$ production for differences in body mass, and we fitted three sets of four models assuming multiplicative, log-normal, heteroscedastic error and additive, normal, homoscedastic or heteroscedastic error[24] (appendix 2 table S2). All models included $CO_2$ production as the dependent variable and body mass as the predictor variable; adjustment for sex (coded 0 for male and 1 for female participants) was included as a categorical covariate. The complete SAS code is available in the appendix 1 (pp 13–15). We used body mass and sex in our model based on the fact that human metabolic $CO_2$ production in energy balance is almost entirely explained by total energy expenditure and respiratory quotient.[11,27] Variables such as body mass, sex, and age accounted for a substantial proportion of variation in total energy expenditure and is confirmed by empirical data.[28]

For more on **IAEA**, see https://www.dlwdatabase.org/

Generalised additive modelling of time-series data for human body mass and per capita $CO_2$ production was conducted for descriptive purposes using the mgcv package. Cumulative sums were derived for global human $CO_2$ production, expressed as unadjusted total $CO_2$ production, and a scaled total $CO_2$ production per unit of body mass using the dplyr package available in R (version 4.5.2). Finally, error propagation uncertainty analyses were conducted as sensitivity analyses to describe production estimates given the uncertainties associated with relevant input variables using the propagate package (appendix 1 p 6).

See Online for appendix 1

### Role of the funding source

The funder had no role in study design, data collection, data analysis, data interpretation, manuscript writing, or decision to submit for publication.

## Results

We performed the allometric modelling of human $CO_2$ production (kg per year) using 9006 measurements from 6756 participants (4479 women and 2277 men; figure 1A; appendix 2 table S1, table S3, and table S4) in the IAEA

DLW database to derive predicted estimates of human $CO_2$ production adjusted for differences in body mass and sex.

The best of 12 competing allometric models (figure 1B, appendix 2 table S2) indicated a non-linear relationship between human $CO_2$ production (Y) and body mass (X):

$$rCO_2 = 25{\cdot}028 \times \text{body mass}^{0{\cdot}62} \times \exp(\text{sex} \times -0{\cdot}18).$$

The adjusted coefficient of determination (adjusted $R^2$) for the best model was 0·603, and the raw residuals from this model plotted against the predicted values were well-behaved and indicated adequate model fit (appendix 2 table S2; appendix 1 pp 9–10).

For adult men, mean body mass increased linearly from 67·3 kg (95% CI 67·2–67·3) in 1985 to 76·0 kg (75·9–76·0) in 2015, representing an increase of approximately 13% (figure 1D). Mean body mass for adult women also increased linearly from 59·8 kg (59·7–59·9) in 1985 to 67·8 kg (67·7–67·9) in 2015, representing approximately 13% increase (figure 1D). In contrast, mean body mass of boys (1–17 years old) displayed a more sigmoid-shaped increase from 36·8 kg (95% CI 36·7–37·0) in 1985 to 41·8 kg (41·7–41·9) in 2015; a similar increase was observed in girls of same range, from 36·4 kg (36·2–36·5) in 1985 to 40·1 kg (40·0–40·2) in 2015. Global population size increased from 1985 to 2015 (figure 1C), which was mostly accounted for by increases in Africa and Asia (figure 1E) for both male and female participants (figure 1E).

As of 2015, human metabolism was responsible for 2·05 Gtonnes of $CO_2$ per year ($GtCO_2$ per year), which represents a 74% increase from 1·18 $GtCO_2$ per year in 1985. Sensitivity analyses illustrated that the assumed input error-derived uncertainty in global human $CO_2$ production ranged from 1·09 $GtCO_2$ per year to 1·28 $GtCO_2$ per year in 1985 and 1·91 $GtCO_2$ per year to 2·27 $GtCO_2$ per year in 2015 (appendix 2 table S6 and table S7). This increase appeared almost entirely because of an increase in contribution from adults (aged ≥18 years) rather than any other age category (figure 2A), which holds when examining human metabolic $CO_2$ production adjusted for differences in body mass (figure 2B). Further, most temporal increase in human metabolic $CO_2$ production can be explained by population expansion because the expected annual per capita human metabolic $CO_2$ production only increased from a mean of 228·5 kg per year (95% CI 228·1–229) in 1985 to 244·9 kg per year (244·5–245·4) in 2015 for juveniles (1–17 years old) and from 320·7 kg per year (320·3–321·1) in 1985 to 346 kg per year (345·6–346·5) in 2015 for adults. This corresponded to an approximately 7–8% increase in per capita $CO_2$ production (figure 2C). Further, the total human metabolic $CO_2$ production adjusted for differences in body mass displayed a 48% increase from 1985 to 2015, thereby accounting for 62% of the temporal increase (figures 2D and 2E).

Despite a larger body mass on average, the total contribution to global human metabolic $CO_2$ production from adult men was similar to that of adult women (within 5%), and this finding was also reflected across all age groups and across time (figure 2B–C). Adult men contribute 7% more than women on a per capita basis (expected 358 kg per year in men *vs* 334 kg per year in women as of 2015; figure 2C), which is attributed to a higher body mass. When adjusted for body mass, women contribute 9% more than men to total metabolic $CO_2$ production (figure 2D); this contribution is accounted for by an increase in the total number of women with a longer average life span than men, as this small difference is almost completely accounted for when expressed on a per capita basis (figure 2E). Thus, men and women provide roughly equivalent contributions to global human metabolic $CO_2$ production. Frequency distributions, reported as kernel density curves, are shown in appendix 1 (p 11).

From 1985 to 2015, China and India accounted for most of the human metabolic $CO_2$ production. In addition, when considering the top ten countries with the highest levels of human metabolic $CO_2$ production in 2015, the combined contribution of China and India (744 Mt per year) greatly exceeded the combined contribution of the other eight countries (458 Mt per year from Bangladesh, Brazil, Indonesia, Japan, Nigeria, Pakistan, Russia, and the USA; figure 3A). Among these countries, the only one that remained in the top ten when expressed as per capita was the USA (figure 3A). Asia accounted for the majority of human metabolic $CO_2$ production (figure 3A, B). This finding persisted when adjusting for body mass (figure 3D), with similar region-specific patterns across men and women (figure 3C, E).

Because dietary food quotient will influence $CO_2$ production independent from body mass, we explored the potential for food quotient (driven primarily by carbohydrate content of the diet) to influence regional differences in human metabolic $CO_2$ production, alongside sex differences and temporal differences using the global dietary database.[29] Substantial regional variation was observed among the food quotient values (kg per year) and in the percent of energy from dietary carbohydrate (figure 3G), with few sex-based (figure 3H), temporal, or differences across age ranges (figure 3I). The variation in percent energy from carbohydrate across time and population age was less than 3%, which would result in a variation in food quotient (and thus respiratory quotient and $CO_2$ production) of less than 1%.

To show the negligible effect of this factor, the biggest difference between regions in terms of percentage energy from carbohydrate resulted in a difference of 0·88 to 0·92, which would alter the estimates of adult per capita human metabolic $CO_2$ production by less than 16 kg per year and of global human metabolic $CO_2$ production by less than 0·1 Gt per year. These variations represent much less than 10% of the difference in human metabolic $CO_2$ production between the continents with the largest difference in total human metabolic $CO_2$ production, Asia and Oceania.

The increase in metabolic $CO_2$ production via increase in the number of humans and increased human body mass[8] could be partly offset by carbon sequestration in those

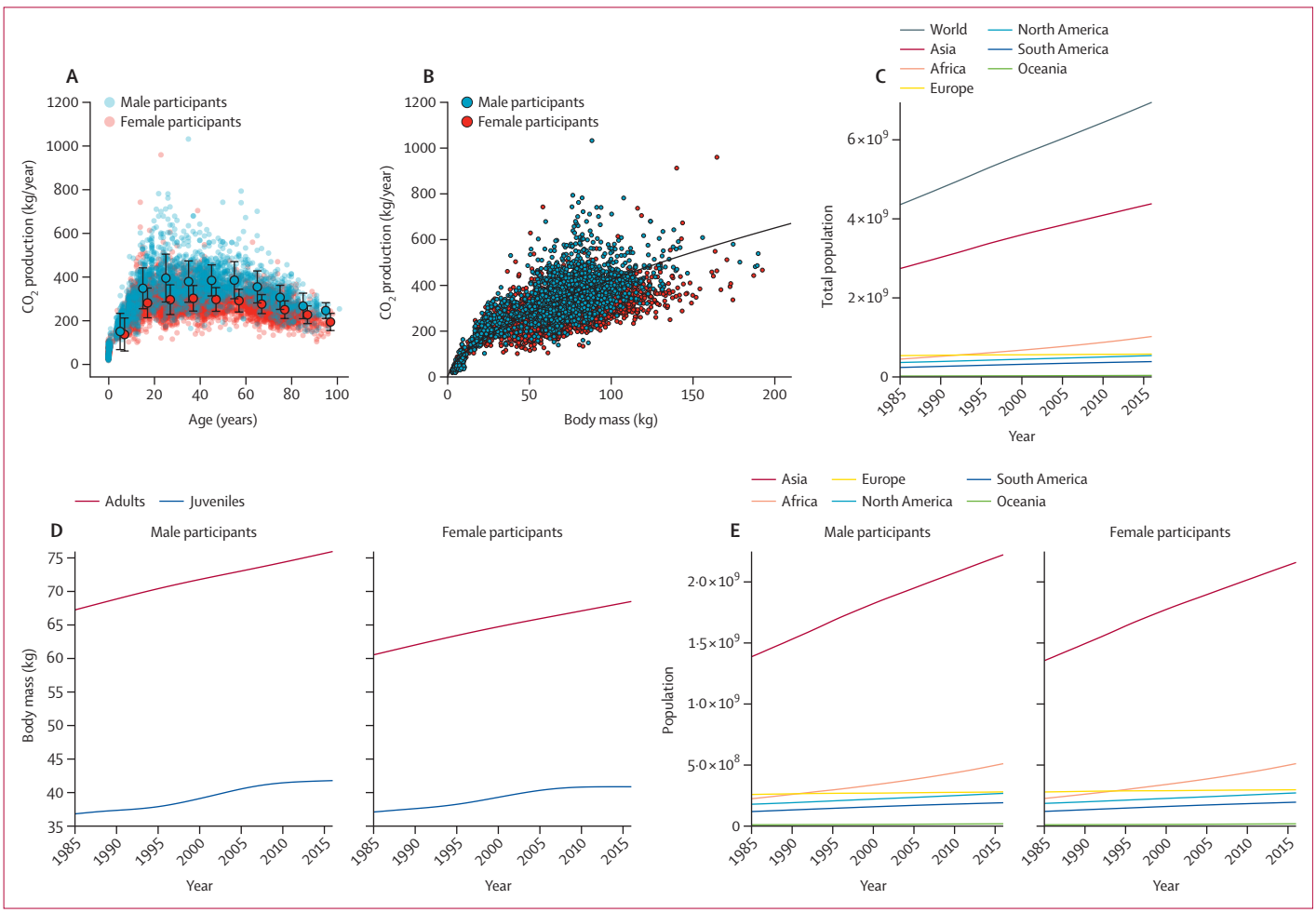


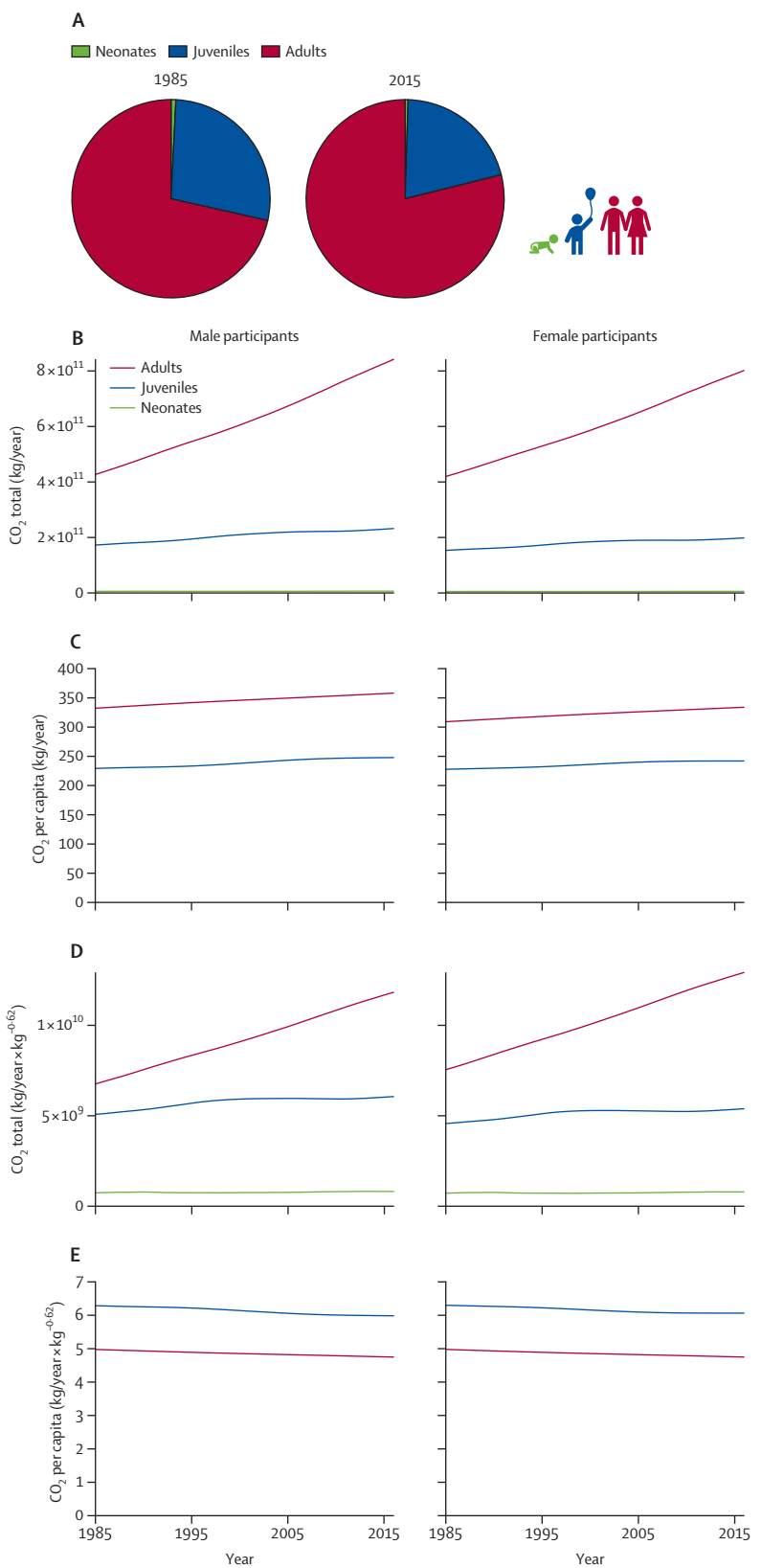

***Figure 1:*** **$CO_2$ production rates of 4479 female and 2277 male participants measured using doubly labelled water**

$CO_2$ production rates plotted against age (mean±95% CI with individual data; A) and body mass (individual data; (B). (C) Estimated population size by continent (cumulative sums). (D) Estimated body mass of male adults (≥18 years) and juveniles (1–17 years) and female adults and juveniles between 1985 and 2015 (mean±95% CI). (E) Estimated population size of male participants and female participants by continent (cumulative sums).

people (temporary storage in human biomass until post-mortem decomposition). We described the potential effect of this factor using previous estimates of human carbon composition[30] and provided additional context against the contribution of food supply chain, and of fossil fuels and land-use change to global $CO_2$ emissions.[1] Moreover, the sequestering of carbon with increases in human biomass has a negligible effect on offsetting human metabolic $CO_2$ production; this sequestration, however, is significant when compared with $CO_2$ emissions from fossil fuels and land-use change, expressed as either a total or per capita (figure 4).

## Discussion

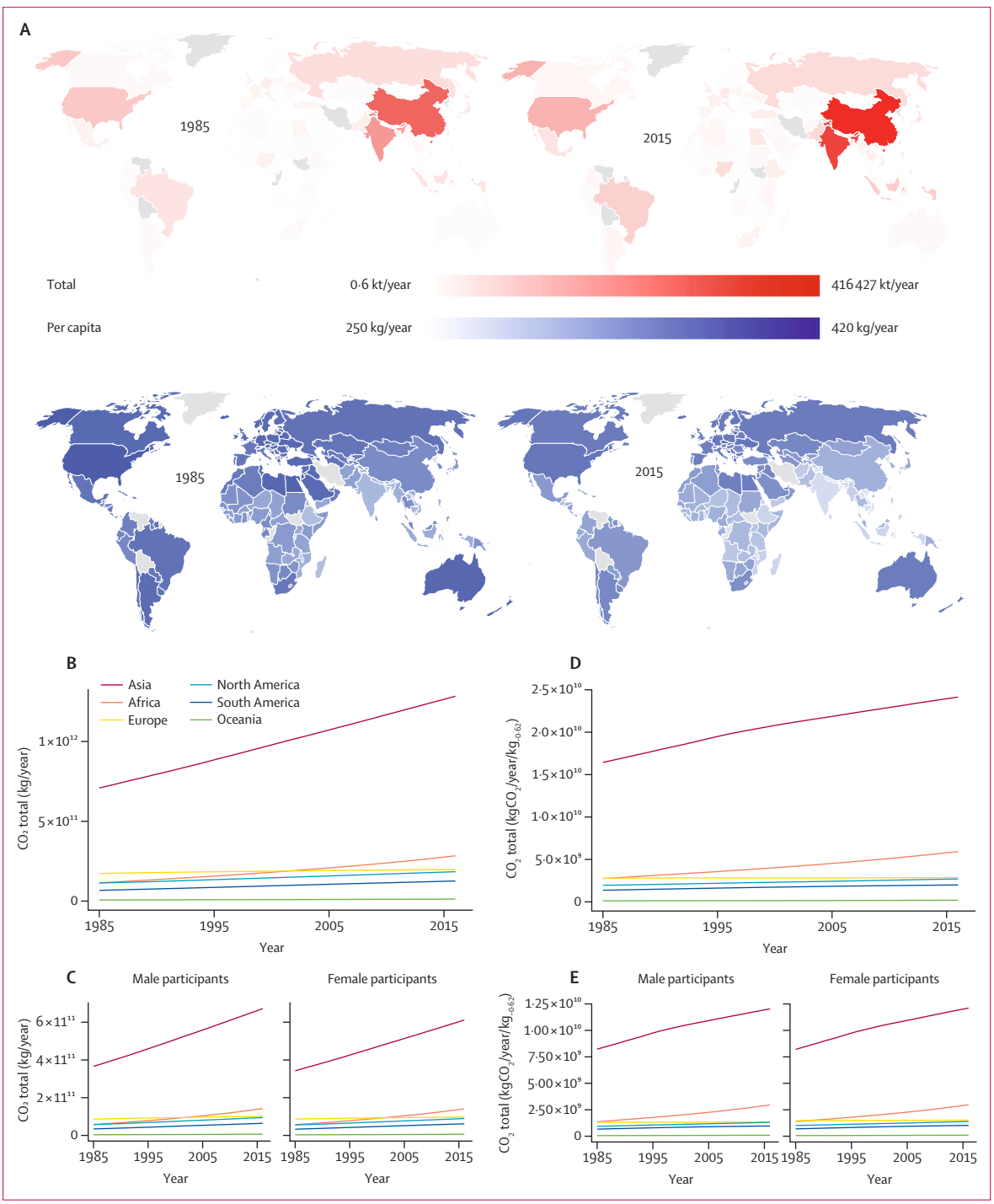
Our study, using measurements of $CO_2$ production quantified in free-living conditions from the IAEA DLW database, revealed that global human metabolic $CO_2$ production almost doubled across the 30-year period from 1985 to 2015. This increase is mostly explained by increased population size, rather than the increase in population body mass or by changes in food quotient or physical activity. These data also show that male participants contributed more human metabolic $CO_2$ production than female participants on an annual per capita basis, consistent with the typically larger body mass of male participants; nevertheless, the longer life span and thus the larger number of women almost completely offsets this difference to result in global human metabolic $CO_2$ production being broadly equivalent between sexes. Over the 30-year analysis period from 1985 to 2015, Africa surpassed Europe as the second largest contributor to global human metabolic $CO_2$ production, which can also be mostly accounted for by increased population size rather than any differences in body mass or food quotient. Although these relative changes over time and between regions are profound, the absolute numbers are also of high magnitude in comparison with other sources of global $CO_2$ emissions.[1,8] Therefore, these data justify the consideration of human metabolism within carbon modelling.




The knowledge and absolute quantification of human metabolic $CO_2$ production have implications for evidence-based decision making regarding global atmospheric $CO_2$ reduction and carbon modelling. Human biogenic carbon cycles are still relevant to total atmospheric $CO_2$ via modulating rates of change (hastening or slowing) when interacting with anthropogenic carbon cycles,[31] and regional carbon flux has implications for climate modelling.[5] Furthermore, estimation of human metabolic $CO_2$ production can contribute to ecosystem scaling of regional net carbon balance, and validate photosynthesis models.[4] Effects on human $CO_2$ emissions associated with metabolism should therefore be considered when estimating the timescale and net effect of interventions designed to reduce obesity or to increase the consumption of carbohydrate-rich, plant-based diets.[7,9–11,32] We show profound relative temporal increases and continent-specific or region-specific differences in human metabolic $CO_2$ production. Moreover, the absolute amount of human metabolic $CO_2$ production (2·05 $GtCO_2$ per year) is substantial in comparison with other sources of $CO_2$ (eg, approximately 5% of anthropogenic $CO_2$) that have any biogenic or anthropogenic flux of ±0·3 $GtCO_2$ per year; these sources are considered relevant for the global carbon budget.[4] Our estimate is broadly similar to estimates based on $CO_2$ production rates of an average young adult.[15,16] However, an understanding of the full effect of the human food system on $CO_2$ emissions requires inclusion of the effects of human metabolism upon consumption of food.

Global human metabolic $CO_2$ production can, in principle, depend on several factors including population size, body mass, dietary food quotient, and total energy expenditure. Our data show that body mass explains most of the variation in per capita human metabolic $CO_2$ production; however, variation in body mass only explains a minor part of variation in population levels of human metabolic $CO_2$ production over time or between regions. The variability in the number of people (specifically adults) is the primary explanation for temporal and regional differences in global human metabolic $CO_2$ production. Temporal and regional variations in total energy expenditure from physical activity or in dietary composition (food quotient) are too small to explain our data.[33] In contrast, global BMI did increase between 1985 to 2015 by approximately 11%.[23] Body mass being the primary predictor of per capita human metabolic $CO_2$ production (adjusted $R^2$ for body mass: 0·50, thus explaining approximately 50% of the variance in human metabolic $CO_2$ production) likely explains a substantial proportion of the increase in per capita human metabolic $CO_2$ production over time.

***Figure 2:*** **Metabolic $CO_2$ contributions from each age category (neonates: aged <1 year; juveniles: aged 1–17 years; adults: aged ≥18 years)**
Percentage contributions to global human metabolic $CO_2$ production in 1985 and 2015 (A), human metabolic $CO_2$ production of each age category and biological sex expressed as a total (cumulative sums) (B), as per capita (mean±95% CI; C), total scaled to per unit metabolic mass (cumulative sums; D), and per capita scaled to per unit metabolic mass (mean±95% CI; E).




(Figure 3 continues on next page)

Existing policies and tools to halt the obesity epidemic, such as the advent of glucagon-like peptide-1 agonists and related drugs, are also therefore relevant to human metabolic $CO_2$ production. However, a 48% temporal increase in global human metabolic $CO_2$ production still remained after adjustment for body mass. Therefore, despite continental or regional differences in body mass and food quotient, population size became the predominant factor dictating differences between continents or regions in human metabolic $CO_2$ production, as normalisation for

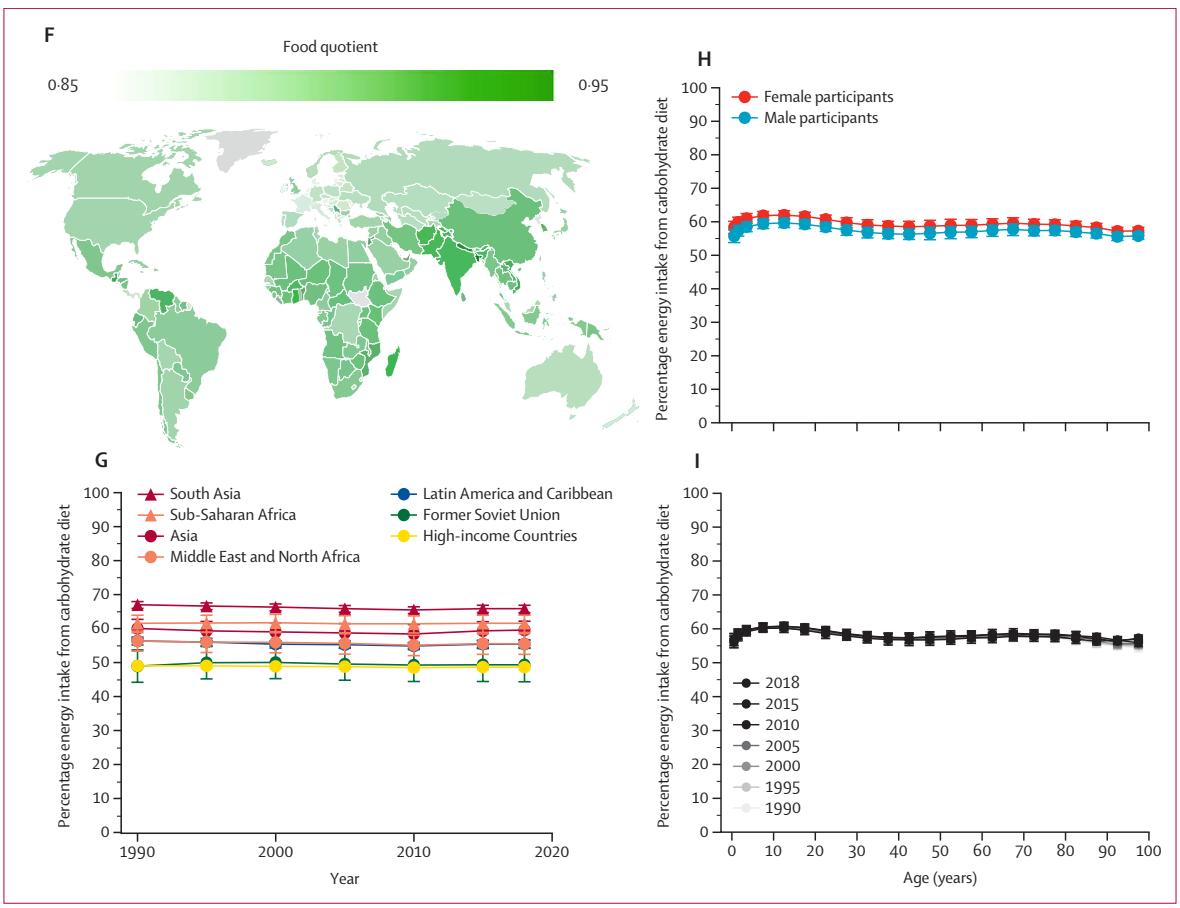
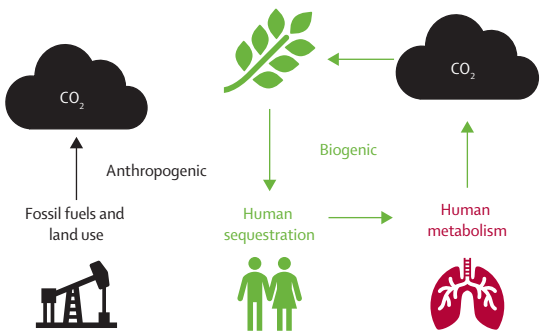



***Figure 3:*** **Contributions from each country to global human metabolic $CO_2$ production**
Contribution as a cumulative sum and per capita in 1985 and 2015 (A), cumulative human metabolic $CO_2$ production of each continent expressed as a total (B), cumulative human metabolic $CO_2$ production of each continent separated by sex (C), cumulative human metabolic $CO_2$ production of each continent scaled to per unit metabolic mass (D), cumulative human metabolic $CO_2$ production of each continent scaled to per unit metabolic mass separated by sex (E), food quotient by country (F), and proportion of energy from carbohydrate by region (mean±95% CI; G), sex (mean±95% CI; H), and age (means±95% CI; I). Data are estimated average means±95% CI.

body mass differences does not alter how human metabolic $CO_2$ production varies between continents or regions, and differences in food quotient make a negligible contribution to intercontinental variance in human metabolic $CO_2$ production. Thus, the general increase in population sizes across the nations and continents, as a result of reduced infant mortality and increased life expectancy, constitutes the predominant factor dictating global human metabolic $CO_2$ production.

Although trends in physical activity or diet cannot explain the temporal (or continental or regional) differences in human metabolic $CO_2$ production reported here, our finding that global human metabolic $CO_2$ production is quantitatively important for $CO_2$ fluxes indicates that there are important implications for modelling population-level changes in behaviour regarding diet and physical activity. This might be expected for physical activity, as it is a major driver of individual levels of $CO_2$ production. However, because most people worldwide are physically inactive,[34] the contribution of physical activity to global $CO_2$ is minor. Nutrition is relevant in the context of dietary guidelines aimed at reducing greenhouse gas emissions during production and transport of food,[9] which have been critiqued with regard to their potential to affect health.[7] For example, decreasing global dietary carbohydrate intake from 60% to 10% of energy (with a food quotient of approximately 0·75; equivalent to that of a ketogenic diet) would reduce the 2015 estimate of human metabolic $CO_2$ production by approximately 12% from 2·05 to 1·8 Gt per year. In contrast, a carbohydrate intake of 72% (with a food quotient of approximately 0·94; equivalent to that of some hunter–gatherer diets[35]) would increase the 2015 estimate of human metabolic $CO_2$ by approximately 5% to 2·15 Gt per year (appendix 1 p 15). Notably, these two diets are extreme, proof-of-principle examples and therefore provides the margins within which more realistic dietary changes are likely to lie within. Furthermore, this estimate ignores the potential for animal-based diets to contribute to greenhouse gas emissions by, for example, methane ($CH_4$) production. Similarly, increasing physical activity with 150 min of moderate walking per week[36] (equivalent to WHO guidelines[37]) would increase the 2015 estimate of human




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| Total $CO_2$ emissions | Absolute number (2015) | 40·9 Gt/year | 0·08 Gt | 2·1 Gt/year |
| | Absolute change (1985–2015) | +15·3 Gt/year | −0·004 Gt/year | +0·9 Gt/year |
| Per-capita $CO_2$ emissions | Absolute number (2015) | 5480 kg/year | 38·9 kg | 346 kg/year |
| | Absolute change (1985–2015) | +220 kg/year | −0·14 kg/year | +25·3 kg/year |

***Figure 4:*** **$CO_2$ emissions from fossil fuel and land-use change,[1] human sequestration, and human metabolism presented as the absolute number (cumulative sum), as an absolute increase, and as a relative increase between 1985 to 2015**

Negative numbers indicate reduced carbon emissions into the atmosphere and increased carbon sequestration within biomass; positive numbers relate to increased carbon emissions into the atmosphere and decreased carbon sequestration within biomass.

metabolic $CO_2$ production by approximately 6% to 2·21 Gt per year, although this might be offset by physical activity-associated reductions in body mass. Increasing physical activity would also contribute to reducing obesity and estimating the effect of obesity reduction by reverting to population levels of body mass to those in 1985, would reduce human metabolic $CO_2$ production by approximately 10% to 1·9 Gt per year. Finally, assuming that the per capita human metabolic $CO_2$ as of 2015 remains constant over time, the increases in population size from 2015 to 2023, will have been responsible for a further increase in human metabolic $CO_2$ to 2·3 Gt per year, that might reach 2·9 Gt per year given the expected peak in global population in 2084.[38] These data therefore do not show that differences in diet composition or physical activity would make any meaningful differences to net $CO_2$ emissions.

Our study aimed to provide a novel description of $CO_2$ production quantified in free-living conditions from the IAEA DLW database, yet not without potential limitations. First, increases in human biomass alongside increases in the human population can likely displace rather than add to other animal biomass, resulting in negligible net change in global animal biomass.[39] Nevertheless, the contribution of human metabolism per se to global $CO_2$ fluxes should be understood. Additionally, for a given biomass, humans might have different rates of $CO_2$ production than other animals, such that with the same global animal biomass, a different ratio of humans to non-human animals produces variance in $CO_2$ flux. Second, $CO_2$ and $CH_4$ are two most quantitatively important radiative gases in Earth's atmosphere. Here, we estimated global $CO_2$ emissions from human metabolism. Although $CH_4$ is a more potent greenhouse gas than $CO_2$ ($CH_4$ is estimated to exert approximately 28 times the greenhouse gas effect than $CO_2$[31]), humans produce much less $CH_4$ than $CO_2$. When expressed as $CO_2$ equivalents (normalising $CH_4$ for the global warming potential to allow direct comparison with $CO_2$), human $CO_2$ equivalents are greater than 99·5% from $CO_2$ and less than 0·5% from $CH_4$.[17] Therefore, the fact that the present analysis is of human metabolic $CO_2$ production alone is unlikely to change the inferences regarding human metabolic contributions to global carbon cycles without considering human $CH_4$ production. Third, the estimates of effects of changing diet, physical activity levels, obesity, and human populations do not include compensatory effects (which would require additional assumptions), and these data do not necessarily suggest that there should be any policies to reduce the consumption of carbohydrate-rich diets, physical activity levels, or the number of humans. Instead, these data provide the means to better model global carbon fluxes with changing human populations and lifestyles. Similarly, the allometric scaling was restricted to body mass rather than including fat-free mass and fat mass. This was because of the absence of available data on global fat-free mass. However, although fat-free mass is a major determinant of resting $CO_2$ production body mass becomes more important during free-living conditions, in which, the cost of movement is related to body mass rather than fat-free mass.

The summary statistics from the error propagation analyses that we conducted for unadjusted and scaled global $CO_2$ production as our primary outcome measures also deserve attention. In this context, the IPCC general carbon emission factors for fossil fuel combustion partly informed our considerations regarding the degree of error for the input variables compounding our primary outcome measures of interest. Fundamentally, such reports informed considerations for error propagation analysis purposes but there is an absence of concrete knowledge about what might constitute the actual degree of error in population

structure data, measurement error and protocol heterogeneity within the IAEA DLW database. Accordingly, interval uncertainty estimation as part of an error propagation analysis remains an inherently exploratory approach suitable for descriptive purposes only, given the general limitations of, for example, Monte Carlo simulation methods[40] and the heterogeneity of procedures that might be considered to conduct such analyses. Future methodological work might seek to explore such issues by systematically characterising uncertainty in key inputs and exploring hierarchical or Bayesian approaches that jointly model parameter, structural, and population-level uncertainty. Another important aspect requiring potential consideration is that the shortage of global representativeness of the DLW database precluded the analysis of potential differences in the scaling relationship between $CO_2$ production and body mass between groups of participants from distinct ethnic backgrounds. Although such an analysis might remain purely exploratory in nature, there are initiatives to address the absence of DLW data from underrepresented populations, and future work might address this. The data that are available indicate that ethnicity-related differences in $CO_2$ production are likely to be small differences related to body mass and age.

The contextual value of the timeframe between 1985 and 2015 might be considered minor in human history; however, the timeframe is important from the viewpoint of the current investigation for three key reasons. First, this timeframe represented rapid but stable population growth; second, this timeframe tracked the global obesity epidemic;[23,25,38] and third, the available data required to carry out this investigation (including data from the IAEA DLW database, databases of country-level population demographic data, and global dietary database) overlap for this timeframe. Although this overlap is not essential for the IAEA DLW database as there is no plausible reason to believe that time would alter the biological relationship between body mass and $CO_2$ production, this does allow accurate modelling with population demographic data and diet data within directly compatible timeframes.

The data in the current investigation show that human metabolism, although rarely acknowledged in carbon models, is a quantitatively important human biogenic source of global atmospheric $CO_2$. Future increases in global population alone are expected to further increase human metabolic $CO_2$ flux. Furthermore, although strategies to reduce obesity have largely been justified on the basis of health benefits, an unforeseen additional benefit could be the reduction of per capita metabolic $CO_2$ production and knock-on effect on the total $CO_2$ flux. Human metabolism should be accounted for to accurately model carbon cycles, and its inclusion in closed-system models, urban carbon budgets, and comparative biogenic flux analyses could enhance the fidelity of carbon accounting. A more nuanced evaluation of human biogenic emissions, including those from human metabolism, might improve our understanding of short-term carbon dynamics and support more comprehensive approaches to climate modelling and sustainability planning.

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JTG conceptualised the original idea; JTG, LL, BS, GA, AM-C, JBu, and EM contributed to data acquisition and analysis; all authors contributed to data interpretation, have approved the final submitted version, and agree to be personally accountable for the work. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication. JTG and LL accessed and verified the data.

**Declaration of interests**
JTG has received research funding from BBSRC (UKRI/BB/C001910/1), MRC (MR/Z505651/1), British Heart Foundation, Clasado Biosciences, Lucozade Ribena Suntory, ARLA Foods Ingredients, Cosun Nutrition Center, Innocent Drinks and the Fruit Juice Science Centre; is a scientific advisory board member to ZOE; and has completed paid consultancy for 6 days Sports Nutrition, Science in Sport, The Dairy Council, PepsiCo, Violicom Medical, Tour Racing, and SVGC. For a full list of disclosures by JTG, see.

JR and ER's institution is supported by NORC Center grant P30 DK072476 titled Nutrition and Metabolic Health Through the Lifespan and by grant U54 GM104940 from the National Institute of General Medical Sciences, which funds the Louisiana Clinical and Translational Science Center.
SB is supported by the National Institute for Health and Care Research (NIHR) Cambridge Biomedical Research Centre (NIHR203312); SB is also supported by the UK Medical Research Council (MC_UU_00006/4). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

**Data sharing**
Data were collected from the International Atomic Energy Agency (IAEA) doubly labelled water (DLW) database and are not publicly available because of restrictions imposed by data sharing agreements. Requests can be made to dlw-database@iaea.org.

**Acknowledgments**
We thank the International Atomic Energy Agency (IAEA; which hosts the IAEA doubly labelled water [DLW] database), Taiyo Nippon Sanso, and SERCON for their financial support. We thank all those who submitted data, including those who are not co-authors or members of the management committee of the DLW database, such as Stephan Branth, Niels C De Bruin, Alice E Dutman, Cara Ebbeling, Mikael Fogelholm, Tamara Harris, Rik Heijligenberg, Hans U Jorgensen, David Ludwig, Gerwin A Meijer, Margaret McCloskey, Daphne L Pannemans, Renaat M Philippaerts, Jacob Plange-Rhule, Elisabet M Rothenberg, Sabine

For more on the **disclosures**, see https://sites.google.com/view/declarationsgonzalez/home

Schulz, Albertine J Scuitt, Albert Stunkard, Amy Subar, Minna Tanskanen, Ricardo Uauy, Giulio Valenti, Rita Van den Berg-Emons, Ludo M van Etten, Wim G Van Gemert, Wilhelmine W Verboeket-van de Venne, and Erica J Velthuis-te Wierik.

Editorial note: The *Lancet* Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

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