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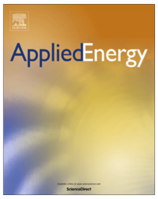

Measurement and analysis of household carbon: The case of a UK city

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HIGHLIGHTS

- Median annual carbon emissions from household end-use energy demand was 6744 kg CO_2e.
- One third of the households were responsible for over half of the carbon emissions.
- There was considerable organic carbon stored in gardens.
- Emissions from transport, gas and electricity demands should all be considered.
- An individual emissions source cannot be used as a marker for high total emissions.

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ABSTRACT

There is currently a lack of data recording the carbon and emissions inventory at household level. This paper presents a multi-disciplinary, bottom-up approach for estimation and analysis of the carbon emissions, and the organic carbon (OC) stored in gardens, using a sample of 575 households across a UK city. The annual emission of carbon dioxide emissions from energy used in the homes was measured, personal transport emissions were assessed through a household survey and OC stores estimated from soil sampling and vegetation surveys. The results showed that overall carbon patterns were skewed with highest emitting third of the households being responsible for more than 50% of the emissions and around 50% of garden OC storage. There was diversity in the relative contribution that gas, electricity and personal transport made to each household's total and different patterns were observed for high, medium and low emitting households. Targeting households with high carbon emissions from one source would not reliably identify them as high emitters overall. While carbon emissions could not be offset by growing trees in gardens, there were considerable amounts of stored OC in gardens which ought to be protected. Exploratory analysis of the multiple drivers of emissions was conducted using a combination of primary and secondary data. These findings will be relevant in devising effective policy instruments for combatting city scale green-house gas emissions from domestic end-use energy demand.

1. Introduction

This paper addresses domestic sector energy consumption, and the measurement of household's carbon and emissions inventory in a UK city.

The Intergovernmental Panel on Climate Change have warned of the global dangers to people and ecosystems of continued green-house gas emissions [1]. Households are one of the largest contributors globally [2] and urban areas are responsible for in excess of 70% of global carbon emissions [3]. Reducing the emissions from households in our cities is a significant international challenge requiring not just energy demand reduction but also by an increase in carbon sinks using 'green space' [4].

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The UK Climate Change Act of 2008 [5] has set a stringent target to reduce national carbon emissions by 80% (on 1990 levels) by 2050 and buildings, transport and planning have been identified as three key areas for action [6]. The measurement of carbon and emissions inventories has been recognised as a key component of policies aimed at emissions reduction [7,8]. There is significant variation in the carbon emissions from households [9] and their rank order distribution demonstrates a tail of high emissions [10]. Higher energy users have greater potential to save energy [11] and emissions reduction policy might therefore best focus on the high emitters first [12], but the identify of high emitting households is not clear.

Signatories to the Kyoto Protocol are required to quantify accurately the national organic carbon (OC) stocks, including those held within urban areas. Previous urban storage estimates in UK carbon inventories were based on untested assumptions and predicted extremely low levels of OC storage in cities and towns, including domestic gardens [13–17]. However, there is increasing evidence that these urban areas are storing much larger quantities of OC than previously recognised [18–22]. It has also been shown that urban gardens offer potential for increasing OC storage in vegetation, due to lower tree cover and a large proportion of small trees in the existing garden population [19]. A question remains as to what proportion of a household's emissions can be offset by their gardens.

There is currently a lack of data recording the carbon and emissions inventory at household level with previous studies limited to a single fuel (e.g. [23]), confounded by results aggregated over hundreds of houses (e.g. [24]), or carried out at the national scale (e.g. [25]). The magnitude of household emissions have been shown to be influenced by a variety of socio-demographic factors including income, vehicle ownership, size of house, the number of occupants and working from home [23,24,26–29]; but the patterns in univariate analysis have not been clear [27].

This paper addresses a gap in the literature by presenting household level carbon emissions and organic carbon inventory results calculated from measurements made during the 4 M project [12]: a study of 575 households across the mid-sized UK city of Leicester, which has a population 330,000 [30]. This custom inventory includes emissions from the 'direct energy' used by the household in their home and personal transport i.e. grid supplied natural gas, grid supplied electricity, and petrol and diesel used in household members' personal transport [31]. It also includes an estimation of the OC stored in the vegetation and soil of each household's garden.

The emissions are reported as an annual rate (kg CO_2e per year) while OC storage accumulates over centuries and is treated as a static total (kg CO_2e). All results are reported per household, rather than per capita, as many emissions, such as those from space heating, are shared within households [32] and follows the recommendation that "future research should perhaps focus more on the household and less on the individual consumer, as the key unit of analysis" ([33] p6118).

This study provides a first assessment of the distributions of carbon emissions, and OC stored in gardens, for different households. It seeks to understand those distributions using multiple, socio-technical characteristics. To the author's knowledge this is the first ever attempt to measure and analyse the variations in households' carbon *and* emissions inventory across a city.

2. Methods

2.1. Study location

Leicester is located in the East Midlands region of England (Fig. 1), it is the 13th largest UK city with c330,00 persons living in 123,100 households [34]. Gross disposable household income was £11,739 per head in Leicester in 2013, compared to a UK average of £17,559 [35]. The city encompasses a land area of approximately 73 km^2 (as defined by the unitary authority boundary) with urban roads, buildings, and other artificial surfaces covering 43% of the land surface while urban green space covers 57% (one third of which is green space in residential gardens) [20]. Leicester experiences average (1981–2010) monthly temperatures of minimum 0.9 °C in February and maximum 22.2 °C in July; annual averages range between 5.9 °C and 13.8 °C, with 1,438 h of sunshine per year and 675 mm of rainfall [36]. Annual carbon emissions within the scope of influence of the local authority (industry, commercial, domestic and road transport) were 5800 kg CO_2 per capita in 2009 for the then population of 304,700, compared with a national total of 6,400 kg CO_2 per capita [37].

2.2. Data collection

The analysis described here used data drawn from the 4 M multi-stage household study [12]. An initial household questionnaire was developed for delivery by an independent social research institute, The National Centre for Social Research (Natcen), using a face-to-face computer-assisted interview format. Questions were designed to collect details about the usage of private (individual/shared) and company cars, home energy use, garden management practices, type of dwelling (e.g. semi-detached, terraced), socio-demographics (e.g. gender, income, occupation) and household composition (e.g. number of people residing in household, age of household members). Additional consent was sought for acquiring

Fig. 1. The East Midlands (shaded grey) and Leicester (shaded black) within England.

gas and electricity meter readings, and monitoring of ambient indoor air temperature [38,39]. The questionnaire underwent piloting, NatCen interviewers received training from the researchers to provide familiarity with the study focus and questionnaire content, and all material received approval by university ethics boards. Individuals could withdraw from the study at any time.

One thousand households were randomly selected from the UK Postcode Address File after stratification, first by percentage of detached houses and then by the average number of dependent children in each of the 36 sub-areas within the city (census-based middle layer super output areas; MLSOA). The 575 participating households (0.5% of households; 57% response rate) were well distributed across the city (Fig. 2) and remained representative of Leicester in terms of the stratification characteristics. The interviewer-administered questionnaire was implemented between March and July 2009. It lasted for approximately 45 min and did not explicitly mention carbon emissions or garden OC storage, mainly to avoid triggering biased responses. Within each household one adult (the household reference person[1] (HRP) or their partner) was interviewed. Additional household-level data were collected through a combination of: follow-up visits over a period of 12 months, publicly available secondary data sources, and the use of a Geographical Information Systems (GIS) with electronic mapping products.

The household characteristics used for the analyses presented here are shown in Table 1. Information about tenure (e.g. owned/rented), number of occupants in the household (dependent children, adults – defined as individuals over the age of 16), age of the HRP, annual household income (before deductions), house type (detached, semi-detached, end-terrace, mid-terrace, converted flat, purpose built flat), and number of vehicles owned came from the initial questionnaire. House type was verified during a follow-up field survey and the use of Google images along with OS MasterMap data in a GIS. Floor area was calculated from the building footprint shown in OS MasterMap using a GIS, and accounting for the number of floors declared in the initial questionnaire. Total area and land cover (e.g. herbaceous vegetation, shrubs, trees, artificial surface) within each household's garden were determined using the OS MasterMap and Landbase datasets in a GIS. Council tax bands, the mechanism for taxation of domestic properties in the UK, were retrieved for each house in the study from the UK Valuation Office Agency website [40] and were used as a proxy for the value of the property.

2.3. Calculating carbon emissions and OC stored in gardens

2.3.1. Emissions from household gas and electricity use

The energy used by each household (heating, hot water, lighting, cooking, and electrical appliances) was calculated from the gas and electricity meter readings. This information was primarily obtained by manually reading the meters at the property up to three times over the first year of the study; when it was not possible to get these readings, mandates signed by the householder enabled the previous year's billing data to be obtained. The first meter reading was recorded by the interviewer during the initial questionnaire. The second reading was recorded by householders in response to a letter request in October 2009; a reminder letter was sent where required. The third meter reading was obtained by a team of researchers during four weeks of house visits in June 2010 and, for the houses that could not be accessed, a further letter request was sent to the households in July 2010.

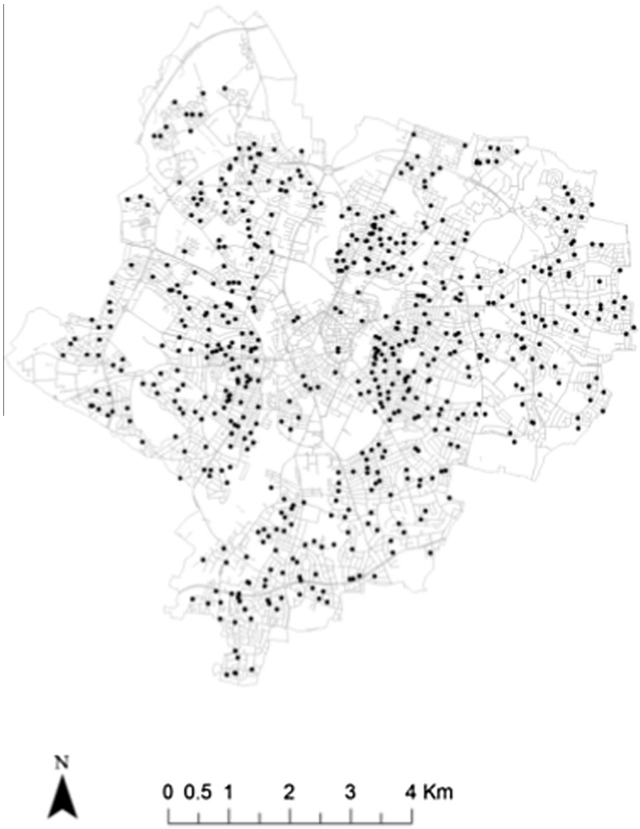

Fig. 2. The approximate location (The location of each house has been randomly perturbed by +/− 100 m in each direction to maintain the anonymity of the participants) of the 575 households within the Unitary Authority Boundary of Leicester and the major road network within the city (52°38′N, 1°08′W).

Table 1
Household characteristics used in the analysis of household emissions.

Variable	Source
Tenure	Initial questionnaire
Number of adults	Initial questionnaire
Number of dependent children	Initial questionnaire
Age of Household Reference Person	Initial questionnaire
Household income	Initial questionnaire
House type	Initial questionnaire- verified by researchers
Number of vehicles	Initial questionnaire
Floor area	OS MasterMap
Garden artificial surface area	OS MasterMap and Landbase
Council tax band	UK Valuation Office Agency

The meter readings provided an estimate of gas usage for 313 households, of which 11 did not use gas (i.e. zero consumption), and electricity usage for 321 households. This resulted in a subsample of 287 households for which both gas and electricity usage were successfully computed (including those with zero gas consumption). All measurements were normalised to produce annual energy demand and associated emissions for the year 2009. Gas normalisation was carried out using the National Grid's 'composite weather variable' (CWV) for the East Midlands 'local distribution zone' (EM LDZ). The CWV is a unique indicator of the daily weather in each LDZ such that there is a linear relationship with the non-daily metered (NDM) gas demand in that LDZ. The CWV is used by the National Grid for historic modelling and for forecasting future demand. It is calculated from two-hourly temperatures and four-hourly wind speeds and includes components for weather history (yesterday's temperatures and seasonal normal temperatures), wind chill, cold weather extremes and summer cut off

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[1] The HRP was defined as the owner/renter of the property, or the person with the greatest income if co-owned/rented, or the oldest co-owner/renter if both had the same income.

[41]. Historic daily values for the CWV and NDM gas demand were downloaded from the National Grid's website [42]. For electricity consumption the results were scaled linearly to 365 days. Finally, annual energy consumption was converted to CO_2e emissions using conversion factors of 0.184 kg CO_2e per kW h of natural gas and 0.544 kg CO_2e per kW h of grid electricity [43].

2.3.2. Emissions from household personal transport use

The carbon emissions from personal transport were calculated from responses to questions in the initial household questionnaire that identified the vehicle specification and usage for up to five vehicles per household. Vehicle specification included make, model, engine size, age, and fuel type. Usage included the occupancy and frequency for journeys that were split into the following categories: very short (0–3 miles), short (3–8 miles), medium (8–50 miles) and long (more than 50 miles). Those responses with incomplete car specifications ($n = 9$) were replaced with an 'average car' based on the UK vehicle licensing statistics for passenger cars [44].

These data were used to calculate 'ultimate' carbon emissions from published average speed emission factors from road vehicles [45] for typical journeys on urban roads in the UK (speed limit of 30 mph (48.28 km/h)). The premise of this calculation is that all the carbon in the fuel will *ultimately* produce CO_2 in the atmosphere [46]. For consistency, the estimated carbon emissions were converted into CO_2e based on the additional emissions of CH_4 and N_2O assumed for the 2009 vehicle fleet [47]. The calculation accounted for cold starts in winter months which significantly increase carbon emissions for the short and very short journeys; these additional emissions were estimated using the assumptions in the EXEMPT (Excess EMissions Planning Tool) model [48]. This model overcomes some of the limitations of the TRAMAQ3 cold start emission model [49] by including the changes in emissions standard from Euro 2 to Euro 4 vehicles. Cold start emissions were directly output as CO_2e.

2.3.3. OC stored in household gardens

To estimate the OC stored in each household's garden, 50 roads across the city of Leicester were randomly selected in a GIS. Each road was visited and permission to sample within one garden was sought whenever there were houses in that road. Sampling included a survey of the vegetation in the entire back garden of the property. All tree species were identified and tree height and diameter at breast height (DBH), 1.3 m, were recorded (see Davies et al. [19] for detailed methodology).

Within each garden, soils were sampled in the dominant vegetation cover types, specifically herbaceous vegetation (predominantly garden lawns) and from beneath shrubs and/or trees. Replicate soil samples were taken, to a depth of 21 cm, using a specialist corer designed to take undisturbed samples (see Edmondson et al. [20,50] for detailed methodology). Soil samples were dried at 105 °C for 24 h, weighed, homogenised using a ball mill, and then passed through a 1 mm sieve. Fine earth soil bulk density (BD) was calculated after removing the dry weight of any matter greater than 1 mm. Homogenised soils were analysed in duplicate for total carbon in an elemental analyser (Vario EL Cube, Elementar, Hanau, Germany). Soil organic carbon (SOC) density was calculated for each individual soil sample using OC concentration and soil density, taking into account the mass of the >1 mm fraction discarded after milling. The figures used for SOC storage in domestic gardens between 0 and 21 cm depth were measured and between 21 and 100 cm were modelled based on a negative exponential relationship derived from 25 samples to 1 m depth taken from across the city. SOC storage was reported to 100 cm, as this is the standard depth used to estimate SOC stock in the national inventory [13].

The detailed garden vegetation and soil surveys were used to derive mean figures for gardens across the city of Leicester, in terms of the mass of carbon per unit land area, of: 0.79 kg/m^2 for above-ground OC; and 27.1 kg/m^2 or 20.2 kg/m^2 for soil OC beneath trees and shrubs or herbaceous vegetation respectively. Of the 575 households that participated in the initial household questionnaire, 469 had gardens. The location of each one was identified in a GIS and the garden boundaries were determined using the Ordnance Survey MasterMap dataset. Within each individual garden, land cover classes were defined using the Landbase dataset (e.g. herbaceous vegetation, tree, shrub, artificial surface). The corresponding areas within each garden were scaled up to estimate the garden OC storage at the individual household level. Total OC stored in gardens was calculated as the sum of soil and above-ground OC and converted to kg CO_2e.

A simple tree planting model, modified from McHugh et al. [51] was applied to those households with gardens ($n = 469$) to estimate their potential for reducing emissions by the sequestration of carbon into biomass as OC. It was assumed that trees could only be 'planted' in herbaceous vegetation (e.g. lawns, flowerbeds), and not in existing patches of trees and shrubs or artificial surfaces (e.g. patios, driveways). The species in the domestic garden tree population in Leicester were determined in a previous survey [19] and split into small trees (mature canopy cover 17 m^2) and large trees (mature canopy cover 68 m^2) [52]. The LandBase GIS dataset provided information on herbaceous vegetation patch size within households' gardens, so that trees were only 'planted' in patches that exceeded their mature canopy cover. Large trees were 'planted' in preference to small trees whenever patch size allowed as they are ultimately capable of storing considerably more OC [19,53]. Small trees were 'planted' in the remaining available space (i.e. where patch size exceeded 17 m^2). The subsequent growth of the virtual trees was modelled for 25 years, using the linear growth functions and biomass calculated using allometric equations described by McHugh et al. [51]. Total biomass was then divided by 25 to give an average annual CO_2 sequestration rate over the course of the 25 year growth period. No account was made of the emissions from any garden maintenance activities that might be carried out by the households.

2.4. Data analysis

Descriptive statistics were used to analyse the distribution of the carbon emissions from household's use of gas, electricity, and personal transport, as well as the combined total emissions and the OC stored in gardens. The households were then ranked by their combined total emissions and divided by the tertiles into low, medium and high groups. This followed a similar approach to the way that others have classified dwellings based on energy use [54,55].

In the next step, the relative contributions that gas, electricity and transport emissions made to each household's combined total emissions was calculated. These were then compared across the high, medium and low total emissions groups to identify if the proportions remained consistent. The results from the tree planting model were used to calculate the potential contribution of carbon sequestration to the reduction of total emissions for households in the high, medium and low groups.

The classification of households by combined total emissions was contrasted with how they would be classified by their gas emissions, electricity emissions, transport emissions and OC stored in the gardens. This was done to identify if classifying households into the high group by one component of the total emissions, or by OC stored in gardens, would be a reasonable proxy for identifying those households in the high combined total emissions group. Confusion matrices were used to calculate the number of true positives (TP), true negatives (TN), false positives (FP), false negatives (FN), true positive rate, false positive rate, and accuracy; following the method described in the literature [56]. For example, for gas emissions: TP is the number of households that are in the high group for gas emissions and also in the high group for combined total emissions, TN is the number of households that are not in the high group for gas emissions and also not in the high group for total emissions, FP is the number of households that are in the high group for gas emissions but not in the high group for total emissions, and FN is the number of households that are not in the high group for gas emissions but are in the high group for total emissions. True positive rate is the fraction of positives that are correctly classified, false positive rate is the fraction of non-positives that are misclassified as positives, and accuracy is the proportion of the entire sample that are either TP or TN.

Exploratory model building was undertaken using multiple linear regressions to examine the relationship between emissions and storage (as outcome variables) and household characteristics (as predictor variables). Stepwise regression was used in order to identify characteristics that significantly predicted each outcome variable. For this purpose the categorical variables were transformed into a single continuous variable: predictor that described house type was recoded to create *Number of Exposed Walls*; household income categories were transformed by taking the midpoint of each income category (all categories had a lower and upper limit) and rounding up to the nearest integer thereby assigning each household a ‘Single Income Value’ [57].

Moderate to strong positive correlations existed among the number of exposed walls and floor area, council tax band and total amount of artificial surface (ranging between $r_s = .451$ to $r_s = .663$). An additional strong positive relationship existed between income and number of vehicles in the household ($r_s = .512$). As none of the correlations were above 0.7, all ten potential predictor variables were included in an initial stepwise regression. The resulting set of statistically significant variables was examined both statistically and for plausibility (based on the authors’ conceptual and empirical knowledge of the outcome variables); the final model was generated from this reduced set of predictors entering all variables at the same time (Enter method).

Regression models were constructed in SPSS version 20 [58]; separate regression analyses were run for each outcome variable. The residual plots from the final regression models were analysed to determine how closely these followed a normal distribution. Where residuals showed large deviations from normality, transformations were applied to the outcome variable, firstly by taking the square root, and then through a logarithmic transformation. The transformation which provided closest behaviour to normality was used in the final results: a natural log transformation for transport emissions, garden storage and combined total emissions; and a square root transformation for electricity emissions [59]. Significance levels were set at $p < 0.05$.

3. Results

3.1. Carbon emissions and OC stored in gardens

The statistics describing annual carbon emissions (gas, electricity, transport and the combined total) and OC stored in gardens are provided in Table 2. Due to variations in questionnaire response, the calculated emissions from gas ($n = 313$), electricity ($n = 321$), and personal transport ($n = 563$) resulted in total emissions figures for a common sample of 281 households. Distributions for all the emissions and OC stored in gardens were positively skewed. Eleven households had no gas emissions (these households used electrical heating), 162 households used no personal vehicle in the previous 12 months, and 106 households had no garden.

The median annual emissions, per household, from gas, electricity and personal transport were 2689 kg CO_2e, 1748 kg CO_2e and 1084 kg CO_2e respectively. The median annual combined total emissions, per household, was 6175 kg CO_2e. The median level of OC stored in household’s gardens was 6744 kg CO_2e.

While these data were not normally distributed, the means are reported for comparison with other data sets and to apply simple scaling. Mean annual emissions, per household, from gas, electricity and personal transport were 2909 kg CO_2e, 2105 kg CO_2e and 1766 kg CO_2e respectively. The mean annual combined total emissions, per household, was 6911 kg CO_2e. The mean level of OC stored in household’s gardens was 9178 kg CO_2e, of which 95% was found to be in the soil. To illustrate the skew in these data: 62% of the households had combined total emissions that were less than the mean for the sample, and 55% had less OC stored than the mean level. Based on 123,100 households in Leicester [34], simply scaling the mean results gives total emissions from all households in the city of approximately 850,744 tCO_2e in 2009. Similarly, the OC stored in all of the cities domestic gardens was 1,129,812 tCO_2e.

3.2. Ranking households

The ranking of households by their combined total emissions (Fig. 3) found that the highest combined total emissions figure for a household was 25 times the lowest. The top 10% of the sample was responsible for 22% of all the emissions and 17% of all OC stored in gardens, whereas the lowest 10% was responsible for only 3% of the emissions and 6% of the OC stored in gardens. This supports policy strategies that would target the reduction of emissions at high emitting households.

There was considerable variation in the relative contribution that gas, electricity, and transport emissions made to households’ combined total emissions. Across the sample ($n = 281$), gas emissions contributed between 0% and 89% of the total emissions for any individual household, with a mean contribution of 46%. For electricity the contribution was between 3% and 100%, with a mean

Table 2
Results for household’s carbon emissions (gas, electricity, transport and the combined total) and organic carbon (OC) stored in gardens.

	Emissions, kg CO_2e per annum in 2009							Storage kg CO_2e	
	Gas		Electricity		Personal transport		Total	Garden OC[+]	
n[*]	313	*281*	321	*281*	563	*281*	*281*	575	*281*
Median	2689	*2687*	1748	*1746*	1084	*1269*	*6175*	6744	*8214*
Mean[†]	2909	*2936*	2105	*2106*	1766	*1870*	*6911*	9178	*10,020*
Interquartile range	1928	*1989*	1480	*1474*	2458	*2264*	*4063*	12,574	*13,352*
Minimum	0	*0*	141	*141*	0	*0*	*990*	0	*0*
Maximum	11,230	*11,230*	13,919	*13,919*	14,947	*14,645*	*24,888*	92,634	*72,345*
Skew	0.89	*0.97*	2.82	*3.02*	2.52	*2.47*	*1.49*	2.74	*2.15*
Kurtosis	2.38	*2.63*	15.13	*17.04*	8.16	*8.34*	*3.17*	11.40	*7.18*

[*] Figures in italics are for $n = 281$, i.e. those houses with results for gas, electricity and personal transport and that are shown in the rank order emissions graph (Fig. 3).
[†] Data are not normally distributed, but the mean is reported for comparison with other data sets.
[+] Garden OC storage figures are not annual emissions.

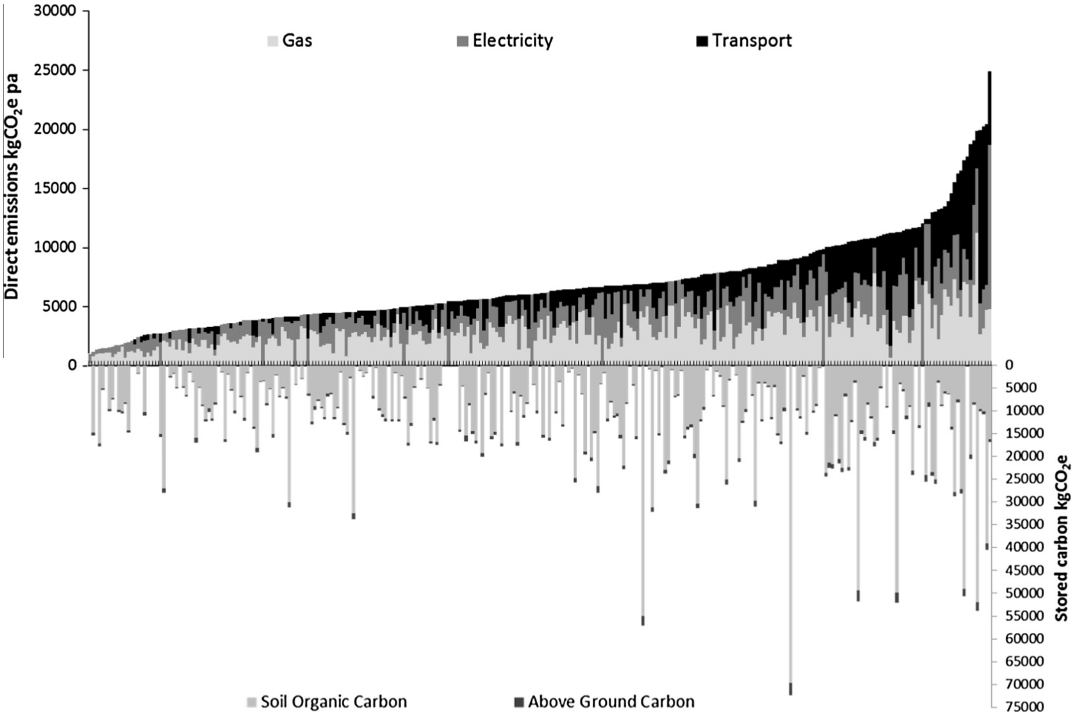

Fig. 3. Rank order stacked bar chart of emissions and organic carbon stored in gardens for 281 households.

Table 3
Pearson correlations between households emissions from gas, electricity and transport, organic carbon (OC) stored in gardens, and total emissions.

		Emissions, kg CO_2e per annum in 2009				Storage kg CO_2e
		Gas	Electricity	Personal transport	Total	Garden OC^{+}
Emissions, kg CO_2e per annum in 2009	Gas	1	0.222**	0.240**	0.634**	0.306**
	Electricity		1	0.281**	0.639**	0.126*
	Personal transport			1	0.807**	0.174**
	Total				1	0.332**
Storage kg CO_2e	Garden OC					1

* Significant at the 0.05 level.
** Significant at the 0.01 level.

of 32%; and for transport the contribution was between 0% and 85% with a mean of 22%. Therefore, on average, emissions from gas made the largest contribution to the combined total while in individual households the largest contributor could be gas, electricity or transport. While transport had the lowest mean contribution it was more strongly correlated with total emissions ($r = 0.81$, $p < 0.01$) than either gas ($r = 0.63$, $p < 0.01$) or electricity ($r = 0.64$, $p < 0.01$) (see Table 3).

Classifying the households into high ($n = 93$), medium ($n = 94$) and low ($n = 94$) groups, based on their rank order for combined total emissions, found that emissions from the high group were 54% of the total from the entire sample and therefore greater than the low and medium groups combined (Table 4). For garden OC storage, the high group contributed 46%, or just below half, of the storage.

The relative contributions of gas, electricity and personal transport emissions to the combined total emissions were different for the three groups (Fig. 4). It can be observed that the proportion of the total emissions that are from gas or electricity falls, on average, from the low to the high group, whereas the proportion of

Table 4
Household's total carbon emissions, organic carbon (OC) stored in gardens, and potential garden tree sequestration by low, medium and high emitters.

Group	Total of emissions		Total of OC stored		Potential sequestration of OC into gardens†	
	kg CO_2e pa	Fraction^{+} (%)	kg CO_2e	Fraction^{+} (%)	kg CO_2e pa	Fraction^{+} (%)
High ($n = 93$)	1,033,263	54	1,289,006	46	1653	0.16
Medium ($n = 94$)	579,925	30	874,074	31	979	0.17
Low ($n = 94$)	328,924	17	652,757	23	829	0.25
Total ($n = 281$)	1,942,112	100	2,815,836	100	3461	0.18

† Average annual total based on potential for tree planting and 25 years subsequent growth.
$^{+}$ Fraction of the total emissions.

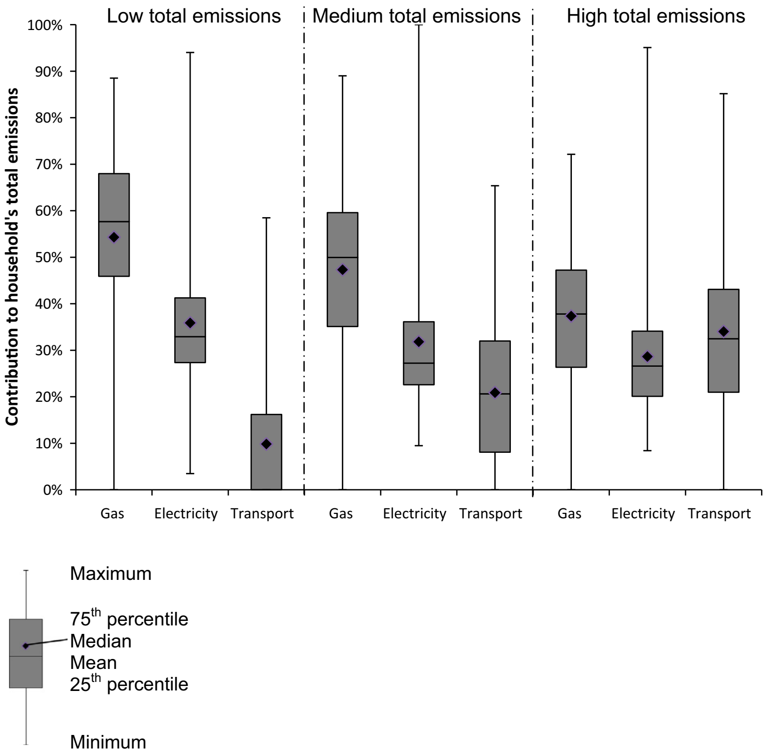

Fig. 4. Box and whisker plot indicating the relative contribution of the three areas of total emissions for households in the low, medium and high total emissions groups.

emissions from personal transport increases on average. While average transport emissions are lower for the whole sample they are comparable with gas and electricity in the high group. This indicates that emissions from personal transport make a considerable contribution to the highest emitting households.

The results from the simple model of garden tree planting revealed that even if all of the households planted trees within their gardens, where feasible, it would make a negligible contribution to reducing the total emissions. In each of the high, medium and low emissions groups, CO_2 sequestration into the newly planted trees would offset the annual emissions by only around 0.2% of the total for that group, when considering annual tree growth averaged over a 25-year period (Table 4). Whilst there is a considerable carbon stock in the domestic gardens of cities, they could not be used to offset the emissions from those households.

The confusion matrices (Tables 5 and 6) indicate how classifying the houses into high, medium and low groups by gas emission, electricity emissions, transport emissions, OC stored in gardens, or gas plus electricity emissions contrasts with their true classification by combined total emissions. Using transport emissions, the true positive rate (76.3%) and the accuracy (84.3%) (see Table 6) was higher than any other single component of the combined total emissions, and similar to when using the gas and electricity emissions total to identify the total emissions classification. This again highlights the relevance of transport emissions to a household's combined total emissions.

Overall these results demonstrate that it would be misleading to consider a household to be a gross high emitter based solely on one component of their combined total emissions.

3.3. Statistical models

The final regression model for each emission type and storage outcome variable was statistically significant (see Table 7). The proportion of variances explained by the identified set of statistically significant predictors were 67% for the transport emissions model, 57% for total emissions, 51% for garden storage, 41% for gas emissions and 27% for electricity emissions. The standardised regression coefficients are directly comparable and provide insight into the relative rank of a predictor in the model [60]. The total number of vehicles in the households and their annual income were statistically significantly positively associated with transport emissions, with vehicle number as the strongest predictor ($\beta = 0.71$, $p < .001$).

Table 5
Confusion matrices contrasting the classification of households by gas emissions, electricity emissions, transport emissions or organic carbon (OC) stored in gardens with their classification by total emissions.

Hypothesised class		True class (total emissions)		
		High	Medium	Low
Gas emissions	High	59	32	2
	Medium	23	36	35
	Low	11	26	57
	Column totals	93	94	94
Electricity emissions	High	63	24	6
	Medium	24	45	25
	Low	6	25	63
	Column totals	93	94	94
Transport emissions	High	71	21	1
	Medium	17	51	26
	Low	5	22	67
	Column totals	93	94	94
OC stored in garden	High	39	36	18
	Medium	34	24	36
	Low	20	34	40
	Column totals	93	94	94
Gas + electricity emissions	High	39	36	18
	Medium	34	24	36
	Low	20	34	40
	Column totals	93	94	94

Table 6
Confusion matrix metrics for 281 houses classified into high medium and low emissions groups ($n = 93$, $n = 94$, $n = 94$ respectively) where true class is based on total emissions (gas + electric + transport).

Hypothesised class	TP	TN	FP	FN	tp rate (%)	fp rate (%)	Accuracy (%)
Gas emissions	59	154	34	34	63.4	18.1	75.8
Electricity emissions	63	158	30	30	67.7	16.0	78.6
Transport emissions	71	166	22	22	76.3	11.7	84.3
OC stored in garden	39	134	54	54	41.9	28.7	61.6
Gas + electricity emissions	70	165	23	23	75.3	12.2	83.6

TP = true positives.
TN = true negatives.
FP = false positives.
FN = false negatives.
tp rate = true positive rate = TP/(TP + FN).
fp rate = false positive rate = FP/(FP + TN).
accuracy = (TP + TN)/(TP + TN + FP + FN).
For more details of these definitions see [56].

The number of adults and dependent children, tenure and the floor area of the house were all significantly positively associated with gas emissions; floor area was the strongest predictor ($\beta = 0.46$, $p < .001$) followed by number of adults ($\beta = 0.24$, $p < .001$). Correspondingly, electricity emissions were significantly positively associated with number of adults and dependent children, council tax and total vehicles; the number of adults was the strongest predictor ($\beta = 0.29$, $p < .001$). Statistically significantly associated predictors of the combined total emissions included number of adults and dependent children, floor area, council tax band and number of vehicles; the latter was the strongest ($\beta = 0.45$, $p < .001$) followed by number of adults ($\beta = 0.25$, $p < .001$). The number of exposed walls, floor area and artificial surface area in the garden were all significantly associated with garden storage; the strongest predictor was the number of exposed walls ($\beta = 0.54$, $p < .001$).

4. Discussion

This paper presents the carbon emissions and OC garden storage for a sample of households in a UK city. It is not unique to measure these quantities, but this is the first time, to the authors' knowledge, that they have been measured together. In the UK, the Department for Energy and Climate Change (DECC) publish annual household gas and electricity emissions, for geographical areas, based on utility bills. The published per household figures for Leicester in 2009 of 2862 kg CO$_2$e for gas and 1952 kg CO$_2$e for electricity are remarkably similar to the results reported here of 2909 kg CO$_2$e for gas and 2105 kg CO$_2$e for electricity. This provides some confidence in the representativeness of the households sampled.

The DECC also publishes transport emissions figures that are modelled for all transport within the city boundary [37]. The published figure for Leicester in 2009 of 5700 kg CO$_2$ per capita equates to approximately 14,108 kg CO$_2$e per household. The result reported here of 1766 kg CO$_2$e per household therefore indicates that the vast majority of transport emissions within the city boundary are not from the personal transport used by the city's resident households. Elsewhere, mean annual household emissions from private car use of 2644 kg CO$_2$ per household for Great Britain, imputed from the National Travel Survey, were reported by Hargreaves et al. [27]. This higher figure may be due to the inclusion of rural areas, whereas the households sampled in this study were urban dwellers potentially driving fewer miles on average.

Table 7
Results for the multiple linear regressions.

Outcome variable	Predictor variables	Coefficient	Standard error	Standardised coefficient	t-value	Significance	Model		
							Adj R^2	F-statistic	Significance
Total emissions[a] ($n = 281$)	Constant	42.48	2.50	–	16.99	<0.001	0.57	75.13	<0.001
	Number of adults	5.36	0.93	0.25	5.77	<0.001			
	Number of dependent children	2.29	0.82	0.11	2.80	0.006			
	Floor area	0.09	0.03	0.17	3.06	0.002			
	Council tax band	2.50	0.96	0.15	2.61	0.010			
	Number of vehicles	11.27	1.17	0.45	9.61	<0.001			
Household gas emissions ($n = 313$)	Constant	67.22	209.73	–	0.32	0.749	0.41	55.16	<0.001
	Number of adults	365.86	68.52	0.24	5.34	<0.001			
	Number of dependent children	228.23	66.99	0.15	3.41	0.001			
	Floor area	18.65	1.88	0.46	9.93	<0.001			
	Tenure (owned)	471.56	159.42	0.14	2.96	0.003			
Household electricity emissions[b] ($n = 321$)	Constant	6.69	0.08	–	83.99	<0.001	0.27	30.71	<0.001
	Number of adults	0.18	0.03	0.29	5.57	<0.001			
	Number of dependent children	0.08	0.03	0.13	2.75	0.006			
	Council tax band	0.09	0.03	0.19	3.65	<0.001			
	Number of vehicles	0.15	0.04	0.20	3.58	<0.001			
Transport emissions[a] ($n = 506$)	Constant	3.75	1.24	–	3.04	0.003	0.67	506.99	<0.001
	Household annual income (£000s)	0.30	0.05	0.18	6.03	<0.001			
	Number of vehicles	21.43	0.89	0.71	24.01	<0.001			
Garden storage[a] ($n = 574$)	Constant	−38.70	5.69	–	−6.80	<0.001	0.51	201.32	<0.001
	Number of exposed walls	36.56	2.58	0.54	14.19	<0.001			
	Garden artificial surface area	0.21	0.04	0.17	4.93	<0.001			
	Floor area	0.19	0.05	0.12	3.51	<0.001			

[a] Square root transformation.
[b] Natural logarithmic transformation.

The mean OC storage, of 9,178 kg CO_2e per household garden, is more than three times higher than currently assumed in urban areas in the English national OC inventory [13]. This demonstrates that small, individually managed and discrete patches of green spaces can enhance citywide OC stocks. The result is commensurate with other recent findings on OC storage in urban gardens as estimated for all gardens across the city [20] and confirms the representativeness of the 575 gardens in this study.

While mean values are used for comparison purposes above, our results show that household emissions are not normally distributed and that the mean is higher than the corresponding median for the emissions individually (gas, electricity, and personal transport) as well as for the OC stored in gardens. The highest one-third of the households had greater total emissions than the other two-thirds combined. Emissions reduction policies could be targeted directly at this high total emissions group, but it may be difficult to identify them from averaged results. Therefore it is suggested that the distributions of emissions figures be reported alongside averaged values in published aggregate emissions statistics, such as sub-national consumption data [61].

The lowest emitting household in the study comprised a single working adult, in a small house and with no personal transport. It is possible that they may have spent periods of time away from home over the period of the study. The highest emitting household comprised three adults in a large house with two cars and a particularly high number of short and very short vehicle journeys, plus high electricity usage. For the households in-between, the relative contributions of gas, electricity, and personal transport to the total carbon emissions varied widely. Emissions from gas were highest across the sample, and highest on average in the high total emissions group. However, the average contribution (mean ratio of a household's gas emissions to their total emissions) was lower in the high group compared to the other two groups. In fact, within the high group the mean contributions of gas, electricity and personal transport to total emissions were relatively similar. Additionally, the confusion matrices demonstrated that the highest emitting households can only be identified reliably from their total emissions and not from any single component. Taken together, these findings substantiate the relevance of reporting total emissions figures that include transport emissions, alongside gas and electricity emissions, in national statistics. Also, they highlight a new opportunity to target a single group of households in order to tackle emissions from both the domestic and transport sectors. Viable technical solutions are readily available, if not easy to implement, and include installing insulation and low carbon heating systems into homes, and a mode shift to public transport.

The data presented for individual garden OC storage provide insight into the contribution that individual houses and their associated gardens can make to the carbon budget of a city. The ratio of the total OC stored in a household's gardens to their total annual emissions ranged from zero to 12.7, with a median value of 1.2 and a mean of 1.7. Non-domestic urban greenspaces can be managed to offset a greater proportion of the CO_2 emitted by households than can domestic gardens, because of the potential to densely plant high yielding tree species such as willow and popular in short-rotation coppice. Over 25 years, the coppice can yield 30 times more carbon sequestration into above-ground biomass per unit area than individual trees of the kinds found in gardens [51]. In Leicester, an area of 5.8 km^2 was recently identified as potentially suitable for short rotation coppice planting, and was estimated to have the potential to sequester 71,800 tonnes of carbon in harvested biomass over 25 years [51]. Nonetheless, estimates of large amounts of carbon stored within gardens demonstrates the valuable service provided by these individual, discrete patches of urban greenspace. The findings highlight the role of individual households in maximising carbon storage potentials by: increasing the greenspace cover and minimising the artificial surface (e.g. paving or decking) within gardens; and managing gardens with minimal reliance on fossil fuel powered machinery.

For cities where residential green space is less common, similar OC storage densities can be provided by non-residential land, such as urban parks [20]. The case for green roofs on building is less clear, though. This study demonstrates that the majority of carbon is stored in the soils. Green roofs tend to be grown on lightweight substrates for obvious structural reasons. Furthermore, it has been shown that trees account for the vast majority of above ground carbon [19] while standard green roofs are based on herbaceous or low-productivity succulent species like *Sedum* and only very rarely are trees grown (and in these cases as pot-plants rather than in roof substrate). Even if we assume that green roofs would not be mown, and might hold a slightly greater above-ground biomass than short-mown grass, the contribution of green roofs, both in aerial extent, and in above-ground biomass carbon, would mean that they would be insignificant contributors to urban ecosystem carbon stores.

The holistic consideration of households' total emissions and garden OC storage, as suggested in this paper, is logical as activities that reduce emissions from one source may increase them in another. For example, a household with electrical space heating may have high carbon emissions from electricity use, while those from gas use are zero. A household member who worked from home may increase the emissions attributed to gas and electricity (for heating, lighting and appliance use within the house) but there could be a consequential reduction in emissions from fuel used driving their car to work. Using a car powered by electricity would remove the emissions attributed to petrol and diesel for personal transport but increase household electricity emissions. Households may pave their front garden to enable off road parking and increase vehicle ownership, while simultaneously reducing above ground OC storage in vegetation and opportunities for further sequestration. In order to reduce the possibility of unintended consequences, and direct or indirect rebound effects, any emissions reduction policy targeting the domestic sector should consider the consequences across a household's entire emissions and OC storage budget. National level data, of the type presented in this study, are needed to support such policy.

The statistical models showed that households with more adults, more children, living in larger and more valuable houses, and owning more vehicles tend to have higher total emissions as would be expected. Household's annual income featured in the transport model, along with vehicle ownership, as a strong predictor of transport emissions. More work is required to understand better what causes emissions in households with high total emissions, but these results indicate the predictive power of complementary datasets.

This study achieved a more holistic evaluation by carrying out the data collection, analysis and interpretation using methods from a number of academic disciplines including transport studies, building energy demand, ecology, and social sciences. Primary data collection was supplemented with secondary data sets, including council tax band and electronic mapping products. Data collection mechanisms such as these are not unique. For example, the English House Condition Survey (a mainly technical study) and the Survey of English Housing (a mainly social study) were joined to produce the English Housing Survey, part of the integrated household survey [62]. Similarly the National Energy Efficiency Data-framework (NEED) [63] combines data from a number of sources, including gas and electricity billing data, and data held by the government's Valuation Office Agency, to produce an extremely valuable resource for building energy research. These existing data sets could be augmented with new questions, or combined with existing data sets, in order to include transport emissions and OC stored in gardens. The UK Department for Transport's Driver and Vehicle Licensing Agency (DVLA) already has a database of car ownership which could, for example, be added to NEED. In this way the cost of providing nationally representative data sets that combine emissions and garden OC storage need not be prohibitively expensive.

5. Conclusions

An in-depth study of 575 households across the city of Leicester in the UK was carried out in 2009 by a multidisciplinary team of researchers. Annual totals of households' carbon emissions from end-use energy demand were summed from: gas and electricity meter readings and self-reported vehicle ownership and trips patterns. Carbon stored above ground in vegetation and in the soil of the gardens was estimated from the results of a unique field trial. Additional socio-demographic and descriptive data were collected from the households and supplemented by secondary data sets.

Median annual household emissions from gas, electricity and personal transport were 2689 kg CO_2e, 1748 kg CO_2e and 1084 kg CO_2e per household per year respectively. The median level of OC stored in household's gardens was 6744 kg CO_2e. The median of the total emissions was 6175 kg CO_2e per household.

The overall carbon distribution patterns were skewed, with the highest emitting third of the households being responsible for more than 50% of all emissions and around 50% of garden OC storage. The relative contribution of gas, electricity and personal transport emissions to the total was shown to vary from household to household. Emissions from gas were dominant on average, but the average contributions from gas, electricity and personal transport were similar in the highest emitting third of the households. There were large amounts of OC stored in households' gardens but the available potential for tree planting in gardens was estimated to provide annual emissions reductions of only 0.2% (based on average sequestration over 25 years of growth in trees reflecting current species composition in gardens and planted at low density in spaces that would accommodate them at maturity). However, more work is needed to understand the causes and predictors of emissions and this might fruitfully concentrate on the high emissions group of households.

The implications of these results for policies that aim to reduce carbon emissions from end-use energy demand in the domestic sector include

- It may be beneficial to target the top third of households by total emissions, as over half of the emissions are from this group.
- Any policy targeting households with high carbon emissions should consider methods to reduce demand for gas, electricity and personal transport together.
- Emission reduction policies would benefit from geographically disaggregated national data sets that report the distributions of emissions totals, as well as the distributions of their components: gas, electricity and personal transport.
- New data sets could be created by combining existing data and data collection mechanisms, or new measurements made in a representative sample of households.
- Contemporaneous socio-demographic data for households are required to understand the predictors of emissions and this could be provided from existing secondary data.

It is also suggested that the considerable amounts of organic carbon stored in household's gardens should be protected.

These findings will be relevant in devising effective policy instruments for combatting global city-scale green-house gas emissions from domestic end-use energy demand in response to warnings from the IPCC.

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