1   **Measurement and analysis of household carbon: the case of a UK city**

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26   **Abstract**

27   This paper presents a multi-disciplinary, bottom-up approach for estimation and analysis of
28   the direct carbon emissions, and the organic carbon (OC) stored in gardens, using a sample
29   of 575 households across a UK city. The direct carbon emissions were those from domestic
30   end-use energy demand by each household: gas, electricity and personal transport. The
31   stored OC was the carbon in the soil and above ground vegetation of each household's
32   garden. The overall carbon distribution patterns were skewed with highest emitting third of
33   the households being responsible for more than 50% of the emissions and around 50% of
34   garden OC storage. Further analysis identified that there was diversity in the relative
35   contribution that gas, electricity and personal transport made to each household's total and
36   different patterns were observed for high, medium and low emitting households. The
37   inclusion of transport emissions was essential to identifying households with high total
38   emissions and demonstrated that targeting households with high carbon emissions from one
39   source alone would not reliably identify them as high gross emitters. While emissions could
40   not be offset by growing trees in gardens, there were considerable amounts of stored OC
41   which ought to be protected. Exploratory analysis of the multiple drivers of direct emissions
42   was conducted using a combination of primary and secondary data. These findings will be
43   relevant in devising effective policy instruments for combatting city scale green-house gas
44   emissions from domestic end-use energy demand.

45   **Research highlights**

46   - Median annual carbon emissions from household end-use energy demand was
47     $6,744 kgCO_2e$
48   - One third of the households were responsible for over half of the direct emissions
49   - There was considerable organic carbon stored in gardens
50   - Emissions from transport, gas and electricity demands should all be considered
51   - An individual emissions source cannot be used as a marker for high total emissions

52   **Keywords**

53   - Domestic energy demand
54   - Household emissions
55   - Transport emissions
56   - Organic carbon storage
57   - Energy policy

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2

1 Introduction

The Intergovernmental Panel on Climate Change have warned of the global dangers to people and ecosystems of continued greenhouse gas emissions (IPCC 2014). The UK Climate Change Act of 2008 (Great Britain 2008) has set a stringent target to reduce national carbon emissions by 80% (on 1990 levels) by 2050. The UK Committee on Climate Change emphasised the important role that local authorities must play in delivering national carbon targets and identified buildings, transport and planning as three key areas for action (Committee on Climate Change, 2012). Urban areas are responsible for in excess of 70% of global carbon emissions (International Energy Agency 2008) and the measurement of emissions in cities was recognised as a key component for a proposed policy framework of mandatory city carbon budgets (Salon et al. 2010). The Royal Institute for Chartered Surveyors have recommended the introduction of mandatory carbon emissions budgets for all the local authorities, backed by consistent monitoring of progress (Dixon 2011). Households are responsible for 75% of the emissions from final demand activities in the UK; 30% of which are directly emitted as a result of fuels used in the home and for private vehicles, while 70% occur in the global supply chains of the products consumed (Baiocchi et al. 2010). This study demonstrates a methodology for measuring direct carbon emissions from end-use energy demand for households in a UK city.

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 (Bradley et al. 2005; Arrouays et al. 2001; Milne & Brown 1997; Xu et al. 2011; Cruickshank et al. 1998). However, there is increasing evidence that these urban areas are storing much larger quantities of OC than previously recognised (Pouyat et al. 2006; Davies et al. 2011; Edmondson et al. 2012; Edmondson, Davies, McCormack, et al. 2014; Edmondson, Davies, Gaston, et al. 2014). 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 (Davies et al. 2011). This study includes the measurement of organic carbon stored in the gardens of households.

There is significant variation in the carbon emissions from households (Thumin & White 2008) and their rank order distribution demonstrates a tail of high emissions (Gough et al. 2011). 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 (Baker & Rylatt 2008; Hargreaves et al. 2013; Aydinalp-Koksal &

94   Ugursal 2008; Büchs & Schnepf 2013); but the patterns in univariate analysis have not been

95   clear (Hargreaves et al. 2013). This study provides a first assessment of the distributions of

96   direct carbon emissions and OC stored in gardens, and seeks to understand the distributions

97   using multiple household characteristics.

98   This paper presents findings from the 4M project (Lomas et al. 2011), a study of 575

99   households across the mid-sized UK city of Leicester, which has a population 330,000

100 (Office for National Statistics 2011). Households' direct carbon emissions were calculated

101 from measurements of grid supplied gas (the predominant heating fuel in the UK), grid

102 supplied electricity, and petrol and diesel used in household members' personal transport.

103 Estimation of OC stored in the vegetation and soil of each household's garden was

104 calculated from measurements made across the city. The direct emissions have been

105 reported as an annual rate ($kgCO_2e$ per year) while OC storage is a static total ($kgCO_2e$). All

106 results are reported per household, rather than per capita, as many emissions, such as

107 those from space heating, are shared within households (Druckman & Jackson 2010) and

108 follows the recommendation that "future research should perhaps focus more on the

109 household and less on the individual consumer, as the key unit of analysis" (Hargreaves et

110 al., 2010 p6118).

111 The measurement and reporting of the distributions of total direct carbon emissions from

112 end-use energy demand in households, and the organic carbon stored in their gardens, is

113 not currently undertaken at a national level in the UK. Therefore, the cost effective

114 application of this measurement, using existing data sets and data collection mechanisms, is

115 suggested and the wider implications for emissions reduction policy are considered.

2   Methods

2.1   Study location

118 Leicester is located in the East Midlands region of England (Figure 1), it is the 13th largest

119 UK city with 123,100 households (ONS 2012). The city encompasses a land area of

120 approximately 73 km^2 (as defined by the unitary authority boundary) with urban roads,

121 buildings, and other artificial surfaces covering 43% of the land surface while urban green

122 space covers 57% (one third of which is green space in residential gardens) (Edmondson et

123 al. 2012). Leicester experiences average (1981-2010) monthly temperatures of minimum

124 0.9 °C in February and maximum 22.2 °C in July; annual averages range between 5.9 °C

125 and 13.8 °C, with 1,438 hours of sunshine per year and 675 mm of rainfall (Met Office 2015).

126 Annual carbon emissions within the scope of influence of the local authority (industry,

127 commercial, domestic and road transport) were 5,800 kg CO_2 per capita in 2009 for the then
128 population of 304,700, compared with a national total of 6,400 kg CO_2 per capita (DECC
129 2011).

130 **2.2   Data collection**

131 The analysis described here used data drawn from the 4M multi-stage household study
132 (Lomas et al. 2011). An initial household questionnaire was developed for delivery by an
133 independent social research institute, The National Centre for Social Research (Natcen),
134 using a face-to-face computer-assisted interview format. Questions were designed to collect
135 details about the usage of private (individual/shared) and company cars, home energy use,
136 garden management practices, type of dwelling (e.g. semi-detached, terraced), socio-
137 demographics (e.g. gender, income, occupation) and household composition (e.g. number of
138 people residing in household, age of household members). Additional consent was sought
139 for acquiring gas and electricity meter readings, and monitoring of ambient indoor air
140 temperature (Lomas & Kane 2012; Kane et al. 2015). The questionnaire underwent piloting,
141 NatCen interviewers received training from the researchers to provide familiarity with the
142 study focus and questionnaire content, and all material received approval by university
143 ethics boards. Individuals could withdraw from the study at any time.

144 One thousand households were randomly selected from the UK Postcode Address File after
145 stratification, first by percentage of detached houses and then by the average number of
146 dependent children in each of the 36 sub-areas within the city (census-based middle layer
147 super output areas; MLSOA). The 575 participating households (0.5% of households; 57%
148 response rate) were well distributed across the city (Figure 2) and remained representative
149 of Leicester in terms of the stratification characteristics. The interviewer-administered
150 questionnaire was implemented between March and July 2009. It lasted for approximately
151 45 minutes and did not explicitly mention carbon emissions or garden OC storage, mainly to
152 avoid triggering biased responses. Within each household one adult (the household
153 reference person[1] (HRP) or their partner) was interviewed. Additional household-level data
154 were collected through a combination of: follow-up visits over a period of 12 months, publicly
155 available secondary data sources, and the use of a Geographical Information Systems (GIS)
156 with electronic mapping products.

157 The household characteristics used for the analyses presented here are shown in Table 1.
158 Information about tenure (e.g. owned/rented), number of occupants in the household
159 (dependent children, adults - defined as individuals over the age of 16), age of the HRP,

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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.

160 annual household income (before deductions), house type (detached, semi-detached, end-
161 terrace, mid-terrace, converted flat, purpose built flat), and number of vehicles owned came
162 from the initial questionnaire. House type was verified during a follow-up field survey and the
163 use of Google images along with OS MasterMap data in a GIS. Floor area was calculated
164 from the building footprint shown in OS MasterMap using a GIS, and accounting for the
165 number of floors declared in the initial questionnaire. Total area and land cover (e.g.
166 herbaceous vegetation, shrubs, trees, artificial surface) within each household's garden were
167 determined using the OS MasterMap and Landbase datasets in a GIS. Council tax bands,
168 the mechanism for taxation of domestic properties in the UK, were retrieved for each house
169 in the study from the UK Valuation Office Agency website (Valuation Office Agency 2012)
170 and were used as a proxy for the value of the property.

171 **2.3   Calculating direct carbon emissions and OC stored in gardens**

172 2.3.1   Emissions from household gas and electricity use

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

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

195   extremes and summer cut off (National Grid 2007). Historic daily values for the CWV and

196   NDM gas demand were downloaded from the National Grid's website (National Grid 2010).

197   For electricity consumption the results were scaled linearly to 365 days. Finally, annual

198   energy consumption was converted to CO_2e emissions using conversion factors of 0.184 kg

199   CO_2e per kWh of natural gas and 0.544 kg CO_2e per kWh of grid electricity (Carbon Trust

200   2009).

201   2.3.2   Emissions from household personal transport use

202   The carbon emissions from personal transport were calculated from responses to questions

203   in the initial household questionnaire that identified the vehicle specification and usage for

204   up to five vehicles per household. Vehicle specification included make, model, engine size,

205   age, and fuel type. Usage included the occupancy and frequency for journeys that were split

206   into the following categories: very short (0-3 miles), short (3-8 miles), medium (8-50 miles)

207   and long (more than 50 miles). Those responses with incomplete car specifications (n=9)

208   were replaced with an 'average car' based on the UK vehicle licensing statistics for

209   passenger cars (DfT 2011).

210   These data were used to calculate 'ultimate' carbon emissions from published average

211   speed emission factors from road vehicles (Defra 2009) for typical journeys on urban roads

212   in the UK (speed limit of 30 mph (48.28 km/h)). The premise of this calculation is that all the

213   carbon in the fuel will *ultimately* produce CO_2 in the atmosphere (CERC 2011). For

214   consistency, the estimated carbon emissions were converted into CO_2e based on the

215   additional emissions of CH_4 and N_2O assumed for the 2009 vehicle fleet (AEA 2009). The

216   calculation accounted for cold starts in winter months which significantly increase carbon

217   emissions for the short and very short journeys; these additional emissions were estimated

218   using the assumptions in the EXEMPT (Excess EMissions Planning Tool) model (AEA 2008).

219   This model overcomes some of the limitations of the TRAMAQ3 cold start emission model

220   (Boulter & Latham 2009) by including the changes in emissions standard from Euro 2 to

221   Euro 4 vehicles. Cold start emissions were directly output as CO_2e.

222   2.3.3   OC stored in household gardens

223   To estimate the OC stored in each household's garden, 50 roads across the city of Leicester

224   were randomly selected in a GIS. Each road was visited and permission to sample within

225   one garden was sought whenever there were houses in that road. Sampling included a

226   survey of the vegetation in the entire back garden of the property. All tree species were

227   identified and tree height and diameter at breast height (DBH), 1.3 m, were recorded (see

228   Davies et al. (2011) for detailed methodology).

229   Within each garden, soils were sampled in the dominant vegetation cover types, specifically
230   herbaceous vegetation (predominantly garden lawns) and from beneath shrubs and/or trees.
231   Replicate soil samples were taken, to a depth of 21 cm, using a specialist corer designed to
232   take undisturbed samples (see Edmondson et al. (2012, 2011) for detailed methodology).
233   Soil samples were dried at 105 $^{\circ}$C for 24 hours, weighed, homogenised using a ball mill, and
234   then passed through a 1 mm sieve. Fine earth soil bulk density (BD) was calculated after
235   removing the dry weight of any matter greater than 1 mm. Homogenised soils were analysed
236   in duplicate for total carbon in an elemental analyser (Vario EL Cube, Elementar, Hanau,
237   Germany). Soil organic carbon (SOC) density was calculated for each individual soil sample
238   using OC concentration and soil density, taking into account the mass of the >1 mm fraction
239   discarded after milling. The figures used for SOC storage in domestic gardens between 0 –
240   21 cm depth were measured and between 21 – 100 cm were modelled based on a negative
241   exponential relationship derived from 25 samples to 1m depth taken from across the city.
242   SOC storage was reported to 100 cm, as this is the standard depth used to estimate SOC
243   stock in the national inventory (Bradley et al. 2005).

244   The detailed garden vegetation and soil surveys were used to derive mean figures for
245   gardens across the city of Leicester, in terms of the mass of carbon per unit land area, of:
246   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
247   and shrubs or herbaceous vegetation respectively. Of the 575 households that participated
248   in the initial household questionnaire, 469 had gardens. The location of each one was
249   identified in a GIS and the garden boundaries were determined using the Ordnance Survey
250   MasterMap dataset. Within each individual garden, land cover classes were defined using
251   the Landbase dataset (e.g. herbaceous vegetation, tree, shrub, artificial surface). The
252   corresponding areas within each garden were scaled up to estimate the garden OC storage
253   at the individual household level. Total OC stored in gardens was calculated as the sum of
254   soil and aboveground OC and converted to kg CO_2e.

255   A simple tree planting model, modified from McHugh et al. (McHugh et al. 2015) was applied
256   to those households with gardens (n=469) to estimate their potential for reducing emissions
257   by the sequestration of carbon into biomass as OC. It was assumed that trees could only be
258   'planted' in herbaceous vegetation (e.g. lawns, flowerbeds), and not in existing patches of
259   trees and shrubs or artificial surfaces (e.g. patios, driveways). The species in the domestic
260   garden tree population in Leicester were determined in a previous survey (Davies et al. 2011)
261   and split into small trees (mature canopy cover 17 m^2) and large trees (mature canopy cover
262   68 m^2) (Wu et al. 2008). The LandBase GIS dataset provided information on herbaceous
263   vegetation patch size within households' gardens, so that trees were only 'planted' in
264   patches that exceeded their mature canopy cover. Large trees were 'planted' in preference

265   to small trees whenever patch size allowed as they are ultimately capable of storing

266   considerably more OC (Nowak & Crane 2002; Davies et al. 2011). Small trees were 'planted'

267   in the remaining available space (i.e. where patch size exceeded 17 m^2). The subsequent

268   growth of the virtual trees was modelled for 25 years, using the linear growth functions and

269   biomass calculated using allometric equations described by McHugh et al. (in review). Total

270   biomass was then divided by 25 to give an average annual CO_2 sequestration rate over the

271   course of the 25 year growth period.

272   **2.4   Data analysis**

273   Descriptive statistics were used to analyse the distribution of the direct carbon emissions

274   from household's use of gas, electricity, and personal transport, as well as the combined

275   total direct emissions and the OC stored in gardens. The households were then ranked by

276   their combined total direct emissions and divided by the tertiles into low, medium and high

277   groups. This followed a similar approach to the way that others have classified dwellings

278   based on energy use (Firth et al. 2008; Summerfield et al. 2010).

279   In the next step, the relative contributions that gas, electricity and transport emissions made

280   to each household's combined total direct emissions was calculated. These were then

281   compared across the high, medium and low total emissions groups to identify if the

282   proportions remained consistent. The results from the tree planting model were used to

283   calculate the potential contribution of carbon sequestration to the reduction of total direct

284   emissions for households in the high, medium and low groups.

285   The classification of households by combined total direct emissions was contrasted with how

286   they would be classified by their gas emissions, electricity emissions, transport emissions

287   and OC stored in the gardens. This was done to identify if classifying households into the

288   high group by one component of the total emissions, or by OC stored in gardens, would be a

289   reasonable proxy for identifying those households in the high combined total direct

290   emissions group. Confusion matrices were used to calculate the number of true positives

291   (TP), true negatives (TN), false positives (FP), false negatives (FN), true positive rate, false

292   positive rate, and accuracy; following the method described in the literature (Fawcett 2006).

293   For example, for gas emissions: TP is the number of households that are in the high group

294   for gas emissions and also in the high group for combined total direct emissions, TN is the

295   number of households that are not in the high group for gas emissions and also not in the

296   high group for total emissions, FP is the number of households that are in the high group for

297   gas emissions but not in the high group for total emissions, and FN is the number of

298   households that are not in the high group for gas emissions but are in the high group for total

299   emissions. True positive rate is the fraction of positives that are correctly classified, false

300   positive rate is the fraction of non-positives that are misclassified as positives, and accuracy

301   is the proportion of the entire sample that are either TP or TN.

302   Exploratory model building was undertaken using multiple linear regressions to examine the

303   relationship between emissions and storage (as outcome variables) and household

304   characteristics (as predictor variables). Stepwise regression was used in order to identify

305   characteristics that significantly predicted each outcome variable. For this purpose the

306   categorical variables were transformed into a single continuous variable: predictor that

307   described house type was recoded to create *Number of Exposed Walls*; household income

308   categories were transformed by taking the midpoint of each income category (all categories

309   had a lower and upper limit) and rounding up to the nearest integer thereby assigning each

310   household a 'Single Income Value' (Hout 2004).

311   Moderate to strong positive correlations existed among the number of exposed walls and

312   floor area, council tax band and total amount of artificial surface (ranging between $r_s = .451$

313   to $r_s = .663$). An additional strong positive relationship existed between income and number of

314   vehicles in the household ($r_s = .512$). As none of the correlations were above 0.7, all ten

315   potential predictor variables were included in an initial stepwise regression. The resulting set

316   of statistically significant variables was examined both statistically and for plausibility (based

317   on the authors' conceptual and empirical knowledge of the outcome variables); the final

318   model was generated from this reduced set of predictors entering all variables at the same

319   time (Enter method).

320   Regression models were constructed in SPSS version 20 (IBM 2010); separate regression

321   analyses were run for each outcome variable. The residual plots from the final regression

322   models were analysed to determine how closely these followed a normal distribution. Where

323   residuals showed large deviations from normality, transformations were applied to the

324   outcome variable, firstly by taking the square root, and then through a logarithmic

325   transformation. The transformation which provided closest behaviour to normality was used

326   in the final results: a natural log transformation for transport emissions, garden storage and

327   combined total direct emissions; and a square root transformation for electricity emissions

328   (Tabachnick & Fidel 2013). Significance levels were set at $p < 0.05$.

329

3   Results

3.1   Direct carbon emissions and OC stored in gardens

The statistics describing direct 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 direct 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 direct emissions, per household, from gas, electricity and personal transport were 2,689 kg CO_2e, 1,748 kg CO_2e and 1,084 kg CO_2e respectively. The median annual combined total direct emissions, per household, was 6,175 kg CO_2e. The median level of OC stored in household's gardens was 6,744 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 direct emissions, per household, from gas, electricity and personal transport were 2,909 kg CO_2e, 2,105 kg CO_2e and 1,766 kg CO_2e respectively. The mean annual combined total direct emissions, per household, was 6,911 kg CO_2e. The mean level of OC stored in household's gardens was 9,178 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 direct 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 (ONS 2012), simply scaling the mean results gives total direct 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 direct emissions (Figure 3) found that the highest combined total direct emissions figure for a household was 25 times the lowest. The top 10% of the sample was responsible for 22% of all the direct 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.

362   There was considerable variation in the relative contribution that gas, electricity, and
363   transport emissions made to households' combined total direct emissions. Across the
364   sample (n=281), gas emissions contributed between 0% and 89% of the total emissions for
365   any individual household, with a mean contribution of 46%. For electricity the contribution
366   was between 3% and 100%, with a mean of 32%; and for transport the contribution was
367   between 0% and 85% with a mean of 22%. Therefore, on average, emissions from gas
368   made the largest contribution to the combined total while in individual households the largest
369   contributor could be gas, electricity or transport. While transport had the lowest mean
370   contribution it was more strongly correlated with total direct emissions (r=0.81, p<0.01) than
371   either gas (r=0.63, p<0.01) or electricity (r=0.64, p<0.01) (see Table 3).

372   Classifying the households into high (n=93), medium (n=94) and low (n=94) groups, based
373   on their rank order for combined total direct emissions, found that emissions from the high
374   group were 54% of the total from the entire sample and therefore greater than the low and
375   medium groups combined (Table 4). For garden OC storage, the high group contributed
376   46%, or just below half, of the storage.

377   The relative contributions of gas, electricity and personal transport emissions to the
378   combined total direct emissions were different for the three groups (Figure 4). It can be
379   observed that the proportion of the total direct emissions that are from gas or electricity falls,
380   on average, from the low to the high group, whereas the proportion of emissions from
381   personal transport increases on average. While average transport emissions are lower for
382   the whole sample they are comparable with gas and electricity in the high group. This
383   indicates that emissions from personal transport make a considerable contribution to the
384   highest emitting households.

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

393   The confusion matrices (Table 5 and Table 6) indicate how classifying the houses into high
394   medium and low groups by gas emission, electricity emissions, transport emissions, OC
395   stored in gardens, or gas plus electricity emissions contrasts with their true classification by
396   combined total direct emissions. Using transport emissions, the true positive rate (76.3%)

397 and the accuracy (84.3%) (see Table 6) was higher than any other single component of the
398 combined total direct emissions, and similar to when using the gas and electricity emissions
399 total to identify the total emissions classification. This again highlights the relevance of
400 transport emissions to a household's combined total direct emissions.

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

403 **3.3   Statistical models**

404 The final regression model for each direct emission type and storage outcome variable was
405 statistically significant (see Table 7). The proportion of variances explained by the identified
406 set of statistically significant predictors were 67% for the transport emissions model, 57% for
407 total emissions, 51% for garden storage, 41% for gas emissions and 27% for electricity
408 emissions. The standardised regression coefficients are directly comparable and provide
409 insight into the relative rank of a predictor in the model (Field 2007). The total number of
410 vehicles in the households and their annual income were statistically significantly positively
411 associated with transport emissions, with vehicle number as the strongest predictor ($\beta = 0.71$,
412 $p < .001$).

413 The number of adults and dependent children, tenure and the floor area of the house were
414 all significantly positively associated with gas emissions; floor area was the strongest
415 predictor ($\beta = 0.46$, $p < .001$) followed by number of adults ($\beta = 0.24$, $p < .001$).
416 Correspondingly, electricity emissions were significantly positively associated with number of
417 adults and dependent children, council tax and total vehicles; the number of adults was the
418 strongest predictor ($\beta = 0.29$, $p < .001$). Statistically significantly associated predictors of the
419 combined total direct emissions included number of adults and dependent children, floor
420 area, council tax band and number of vehicles; the latter was the strongest ($\beta = 0.45$, $p
421 < .001$) followed by number of adults ($\beta = 0.25$, $p < .001$). The number of exposed walls,
422 floor area and artificial surface area in the garden were all significantly associated with
423 garden storage; the strongest predictor was the number of exposed walls ($\beta = 0.54$, $p
424 < .001$).

425 **4 Discussion**

426 This paper presents the direct carbon emissions and OC garden storage for a sample of
427 households in a UK city. It is not unique to measure these quantities, but this is the first time,
428 to the authors' knowledge, that they have been measured together. In the UK, the
429 Department for Energy and Climate Change (DECC) publish annual household gas and

430   electricity emissions, for geographical areas, based on utility bills. The published per

431   household figures for Leicester in 2009 of 2,862 kg CO_2e for gas and 1,952 kg CO_2e for

432   electricity are remarkably similar to the results reported here of 2,909 kg CO_2e for gas and

433   2,105 kg CO_2e for electricity. This provides some confidence in the representativeness of the

434   households sampled.

435   The DECC also publishes transport emissions figures that are modelled for all transport

436   within the city boundary (DECC 2011). The published figure for Leicester in 2009 of 5,700

437   kg CO_2 per capita equates to approximately 14,108 kg CO_2e per household. The result

438   reported here of 1,766 kg CO_2e per household therefore indicates that the vast majority of

439   transport emissions within the city boundary are not from the personal transport used by the

440   city's resident households. Elsewhere, mean annual household emissions from private car

441   use of 2,644 kg CO_2 per household for Great Britain, imputed from the National Travel

442   Survey, were reported by Hargreaves et al. (2013). This higher figure may be due to the

443   inclusion of rural areas, whereas the households sampled in this study were urban dwellers

444   potentially driving fewer miles on average.

445   The mean OC storage, of 9,178 kg CO_2e per household garden, is more than three times

446   higher than currently assumed in urban areas in the English national OC inventory (Bradley

447   et al. 2005). This demonstrates that small, individually managed and discrete patches of

448   green spaces can enhance citywide OC stocks. The result is commensurate with other

449   recent findings on OC storage in urban gardens as estimated for all gardens across the city

450   (Edmondson et al. 2012) and confirms the representativeness of the 575 gardens in this

451   study.

452   While mean values are used for comparison purposes above, our results show that

453   household emissions are not normally distributed and that the mean is higher than the

454   corresponding median for the direct emissions individually (gas, electricity, and personal

455   transport) as well as for the OC stored in gardens. The highest one-third of the households

456   had greater total emissions than the other two-thirds combined. Emissions reduction policies

457   could be targeted directly at this high total emissions group, but it may be difficult to identify

458   them from averaged results. Therefore it is suggested that the distributions of emissions

459   figures be reported alongside averaged values in published aggregate emissions statistics,

460   such as sub-national consumption data (DECC 2012).

461   The relative contributions of gas, electricity, and personal transport to the total direct carbon

462   emissions varied widely between households. Emissions from gas were highest across the

463   sample, and highest on average in the high total emissions group. However, the average

464   contribution (mean ratio of a household's gas emissions to their total emissions) was lower in

465   the high group compared to the other two groups. In fact, within the high group the mean

466   contributions of gas, electricity and personal transport to total emissions were relatively

467   similar. Additionally, the confusion matrices demonstrated that the highest emitting

468   households can only be identified reliably from their total emissions and not from any single

469   component. Taken together, these findings substantiate the relevance of reporting total

470   emissions figures that include transport emissions, alongside gas and electricity emissions,

471   in national statistics. Also, they highlight a new opportunity to target a single group of

472   households in order to tackle emissions from both the domestic and transport sectors.

473   The data presented for individual garden OC storage provide insight into the contribution that

474   individual houses and their associated gardens can make to the carbon budget of a city.

475   Whilst it is acknowledged that urban greenspaces cannot be managed to offset a substantial

476   proportion of the CO_2 emitted by households, estimates of large amounts of carbon stored

477   within gardens demonstrates the valuable service provided by these individual, discrete

478   patches of urban greenspace. The findings highlight the role of individual households in

479   maximising carbon storage potentials by: increasing the greenspace cover and minimising

480   the artificial surface (e.g. paving or decking) within gardens; and managing gardens with

481   minimal reliance on fossil fuel powered machinery.

482   The holistic consideration of households' total direct emissions and garden OC storage, as

483   suggested in this paper, is logical as activities that reduce emissions from one source may

484   increase them in another. For example, a household with electrical space heating may have

485   high carbon emissions from electricity use, while those from gas use are zero. A household

486   member who worked from home may increase the emissions attributed to gas and electricity

487   (for heating, lighting and appliance use within the house) but there could be a consequential

488   reduction in emissions from fuel used driving their car to work. Using a car powered by

489   electricity would remove the emissions attributed to petrol and diesel for personal transport

490   but increase household electricity emissions. Households may pave their front garden to

491   enable off road parking and increase vehicle ownership, while simultaneously reducing

492   above ground OC storage in vegetation and opportunities for further sequestration. In order

493   to reduce the possibility of unintended consequences, and direct or indirect rebound effects,

494   any emissions reduction policy targeting the domestic sector should consider the

495   consequences across a household's entire direct emissions and OC storage budget.

496   National level data, of the type presented in this study, are needed to support such policy.

497   The statistical models showed that households with more adults, more children, living in

498   larger and more valuable houses, and owning more vehicles tend to have higher total

499   emissions as would be expected. Household's annual income featured in the transport

500   model, along with vehicle ownership, as a strong predictor of transport emissions. More work

501   is required to understand better what causes emissions in households with high total

502   emissions, but these results indicate the predictive power of complementary datasets.

503   This study achieved a more holistic evaluation by carrying out the data collection, analysis

504   and interpretation using methods from a number of academic disciplines including transport

505   studies, building energy demand, ecology, and social sciences. Primary data collection was

506   supplemented with secondary data sets, including council tax band and electronic mapping

507   products. Data collection mechanisms such as these are not unique. For example, the

508   English House Condition Survey (a mainly technical study) and the Survey of English

509   Housing (a mainly social study) were joined to produce the English Housing Survey, part of

510   the integrated household survey (ESDS n.d.). Similarly the National Energy Efficiency Data-

511   framework (NEED) (DECC 2013) combines data from a number of sources, including gas

512   and electricity billing data, and data held by the government's Valuation Office Agency, to

513   produce an extremely valuable resource for building energy research. These existing data

514   sets could be augmented with new questions, or combined with existing data sets, in order

515   to include transport emissions and OC stored in gardens. The UK Department for

516   Transport's Driver and Vehicle Licensing Agency (DVLA) already has a database of car

517   ownership which could, for example, be added to NEED. In this way the cost of providing

518   nationally representative data sets that combine direct emissions and garden OC storage

519   need not be prohibitively expensive.

520   **5 Conclusions**

521   An in-depth study of 575 households across the city of Leicester in the UK was carried out in

522   2009 by a multidisciplinary team of researchers. Annual totals of households' direct carbon

523   emissions from end-use energy demand were summed from: gas and electricity meter

524   readings and self-reported vehicle ownership and trips patterns. Carbon stored above

525   ground in vegetation and in the soil of the gardens was estimated from the results of a

526   unique field trial. Additional socio-demographic and descriptive data were collected from the

527   households and supplemented by secondary data sets.

528   Median annual household emissions from gas, electricity and personal transport were 2,689

529   kg CO_2e, 1,748 kg CO_2e and 1,084 kg CO_2e per household per year respectively. The

530   median level of OC stored in household's gardens was 6,744 kg CO_2e. The median of the

531   total direct emissions was 6,175 kg CO_2e per household.

532   The overall carbon distribution patterns were skewed, with the highest emitting third of the
533   households being responsible for more than 50% of all emissions and around 50% of garden
534   OC storage. The relative contribution of gas, electricity and personal transport emissions to
535   the total was shown to vary from household to household. Emissions from gas were
536   dominant on average, but the average contributions from gas, electricity and personal
537   transport were similar in the highest emitting third of the households. There were large
538   amounts of OC stored in households' gardens but the available potential for tree planting in
539   gardens was estimated to provide annual emissions reductions of only 0.2% (based on
540   average sequestration over 25 years of growth). However, more work is needed to
541   understand the causes and predictors of emissions and this might fruitfully concentrate on
542   the high emissions group of households.

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

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

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

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

562 **Acknowledgements**

572

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736

737 **Tables**

738 **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

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740

741 **Table 2: Results for household's direct carbon emissions (gas, electricity, transport**
742 **and the combined total) and organic carbon (OC) stored in gardens**

	Emissions, kgCO$_2$e per annum in 2009							Storage kgCO$_2$e	
	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	*10020*
Interquartile range	1928	*1989*	1480	*1474*	2458	*2264*	*4063*	12574	*13352*
Minimum	0	*0*	141	*141*	0	*0*	*990*	0	*0*
Maximum	11230	*11230*	13919	*13919*	14947	*14645*	*24888*	92634	*72345*
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*

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

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

		Emissions, $kgCO_2e$ per annum in 2009				Storage $kgCO_2e$
		Gas	Electricity	Personal transport	Total	Garden OC[+]
Emissions, $kgCO_2e$ 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 $kgCO_2e$	Garden OC					1

[*] significant at the 0.05 level [**] significant at the 0.01 level

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

Group	Total of direct 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%	3,461	0.18%

[†]Average annual total based on potential for tree planting and 25 years subsequent growth
[+]Fraction of the total direct emissions

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

		True class (total emissions)		
Hypothesised class		High	Medium	Low
	High	59	32	2
Gas emissions	Medium	23	36	35
	Low	11	26	57
	Column totals	93	94	94
		High	Medium	Low
	High	63	24	6
Electricity emissions	Medium	24	45	25
	Low	6	25	63
	Column totals	93	94	94
		High	Medium	Low
	High	71	21	1
Transport emissions	Medium	17	51	26
	Low	5	22	67
	Column totals	93	94	94
		High	Medium	Low
	High	39	36	18
OC stored in garden	Medium	34	24	36
	Low	20	34	40
	Column totals	93	94	94
		High	Medium	Low
	High	39	36	18
Gas + electricity emissions	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 emisions	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 (Fawcett 2006).

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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[1] **(n=281)**	Constant	42.48	2.50	-	16.99	<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	0.57	75.13	<0.001
	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			
	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	0.41	55.16	<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[2] **(n=321)**	Constant	6.69	0.08	-	83.99	<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	0.27	30.71	<0.001
	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[1] **(n=506)**	Constant	3.75	1.24	-	3.04	0.003			
	Household annual income (£000s)	0.30	0.05	0.18	6.03	<0.001	0.67	506.99	<0.001
	Number of vehicles	21.43	0.89	0.71	24.01	<0.001			
Garden storage[1] **(n=574)**	Constant	-38.70	5.69	-	-6.80	<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	0.51	201.32	<0.001
	Floor area	0.19	0.05	0.12	3.51	<0.001			

772 [1] Square Root Transformation, [2] Natural Logarithmic Transformation

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Figure 1: The East Midlands (shaded grey) and Leicester (shaded black) within England

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Figure 2: The approximate location[2] 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)

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[2] The location of each house has been randomly perturbed by +/- 100m in each direction to maintain the anonymity of the participants
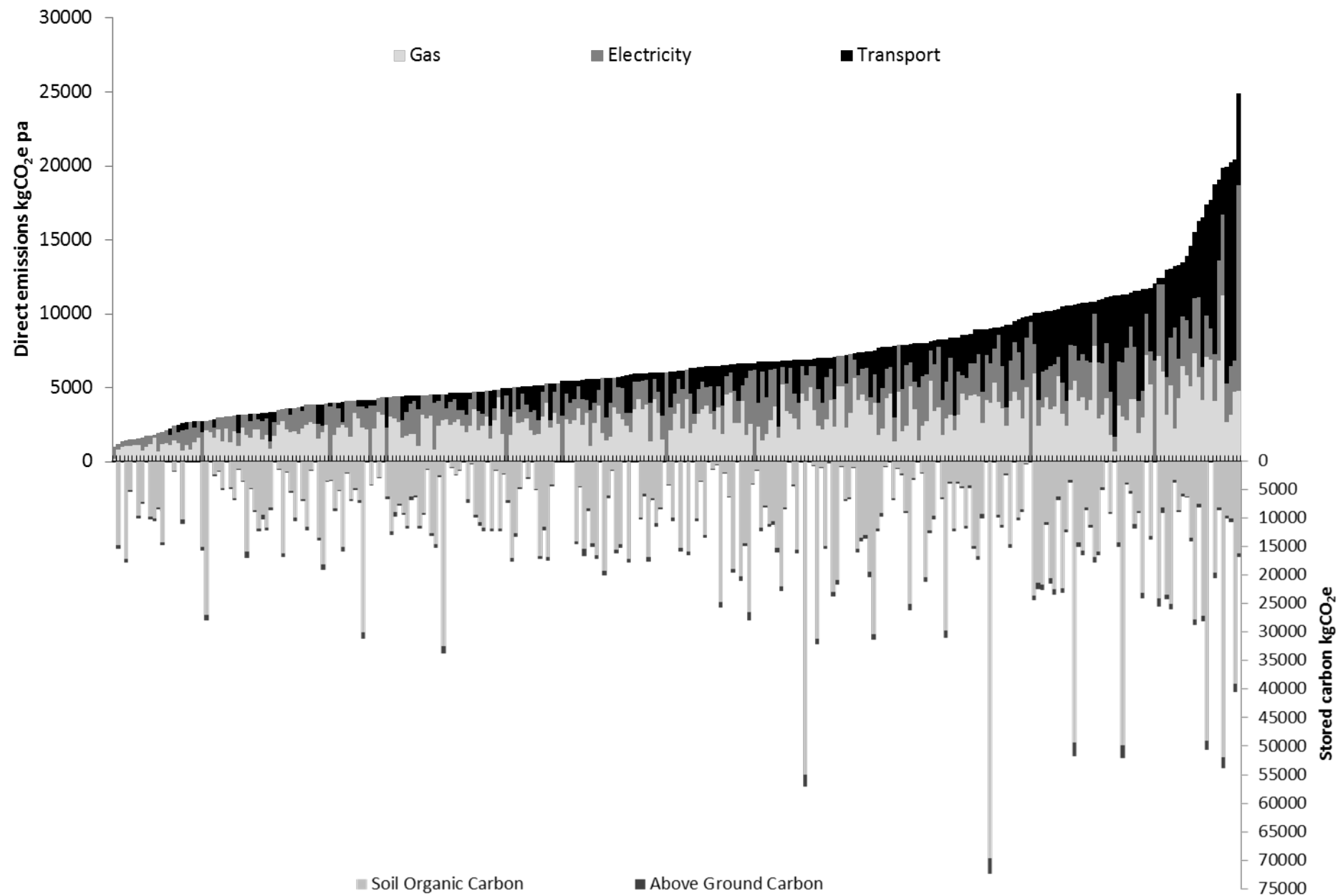
Figure 3: Rank order stacked bar chart of direct emissions and organic carbon stored in gardens for 281 households
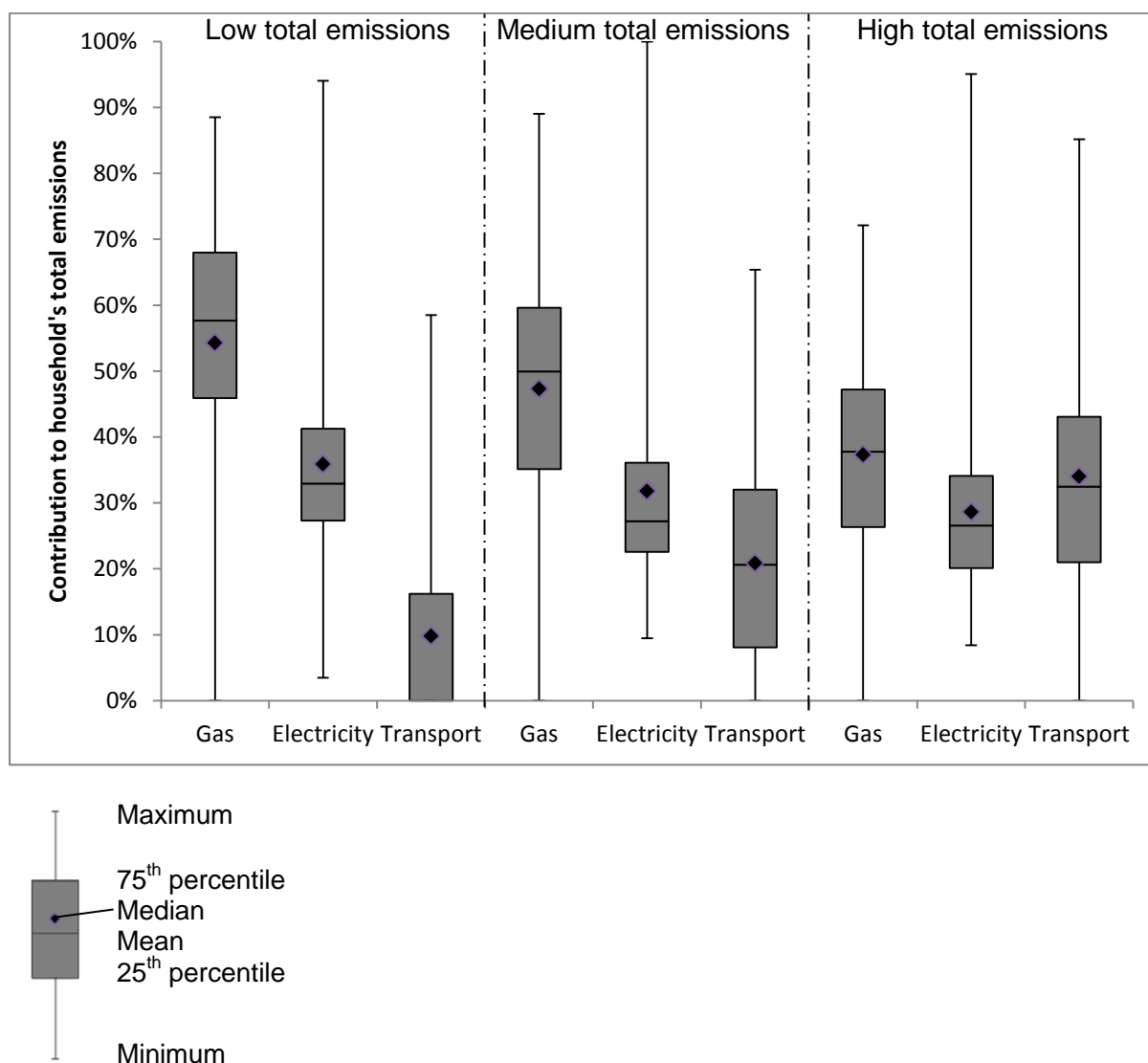
Figure 4: Box and whisker plot indicating the relative contribution of the three areas of total emissions for households in the low, medium and high total emissions groups