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# Quantifying Carbon Footprint Reduction Opportunities for U.S. Households and Communities

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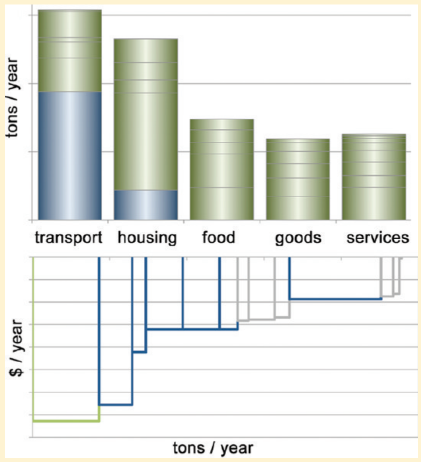
S Supporting Information

**ABSTRACT:** Carbon management is of increasing interest to individuals, households, and communities. In order to effectively assess and manage their climate impacts, individuals need information on the financial and greenhouse gas benefits of effective mitigation opportunities. We use consumption-based life cycle accounting techniques to quantify the carbon footprints of typical U.S. households in 28 cities for 6 household sizes and 12 income brackets. The model includes emissions embodied in transportation, energy, water, waste, food, goods, and services. We further quantify greenhouse gas and financial savings from 13 potential mitigation actions across all household types. The model suggests that the size and composition of carbon footprints vary dramatically between geographic regions and within regions based on basic demographic characteristics. Despite these differences, large cash-positive carbon footprint reductions are evident across all household types and locations; however, realizing this potential may require tailoring policies and programs to different population segments with very different carbon footprint profiles. The results of this model have been incorporated into an open access online carbon footprint management tool designed to enable behavior change at the household level through personalized feedback.




## 1. INTRODUCTION

Voluntary greenhouse gas (GHG) management programs and policies directed at individuals, households, and communities serve as compliments to national and state-level policies directed at heavy industrial emitters.[1,2] Recently there has been a marked increase in information campaigns promoting lower-carbon lifestyles choices, community-based social marketing programs,[3] voluntary carbon offsets programs,[4] and the proliferation of online household carbon footprint calculators[5] aimed at reducing emissions related to individual lifestyles. Several recent studies suggest that voluntary consumer-oriented programs can reduce household carbon footprints by 5−20%.[6−8] However, individuals and program developers need information on the relative contribution of different household activities to household carbon footprints as well as and the financial and GHG benefits of different household mitigation strategies.

In the United States, GHG emissions associated with household consumption have been estimated to account for over 80% of total U.S. emissions and upward of 120% if emissions embodied in imports are adjusted for the carbon-intensity of production.[9−11] An increasing number of studies have further analyzed the size, composition, and the demographic or geographic distribution of household carbon footprints at global, national, and regional scales.[12−14] While modeling techniques have become increasingly sophisticated, this research has not been translated into comprehensive carbon management tools available to households, communities, and small businesses to monitor and quantify emission reduction opportunities. Instead, relevant information available to individuals has been quite general in nature, such as providing lists of tips to reduce carbon footprints, or so-called carbon footprint calculators that only consider a limited portion of total household carbon footprints.[15]

This paper presents a consumption-based accounting model of U.S. household consumption, including GHG emissions released during the extraction, processing, transport, use and disposal phases of household transportation, energy, water, waste, food, goods, and services. Consumption-based accounting provides a comprehensive assessment of emissions related to individual consumer choices[16−18] and is well suited for the development of consumer-oriented carbon management tools.[4,14] Carbon footprints are calculated for households in 28 cities across 6 household sizes and 12 income brackets for a total of over 2000 different household types. Greenhouse gas and financial savings are further quantified for a set of 13 potential mitigation actions across all household types. By applying the same basket of interventions across households with very different carbon profiles we demonstrate the utility of targeting policies and programs to specific geographic and demographic population segments. The results of this model have been incorporated into open access online carbon footprint management tools[19,20] designed to enable behavior change at the

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household level in California[19] and across the United States[20] by providing personalized feedback to users on their carbon footprints.

## 2. METHODS

The total household carbon footprint, HCF, of any individual or population can be expressed simply as the product of consumption, $C$, in dollars or physical units, and emissions per unit of consumption, $E$, summed over each emissions activity ($i$) included in the model

$$\mathrm{HCF} = \sum C_i E_i \quad (1)$$

Total annual household consumption, $C$, for each household type by location, household size, and income is calculated as

$$C = \sum [C_{\mathrm{msa},\,i} * C_{t,\,i} / C_{\mathrm{usa},\,i}] \quad (2)$$

where $C_{\mathrm{msa},i}$ is the average household consumption, in dollars, in each metropolitan statistical area (msa) in the Consumer Expenditures Survey (CES)[21] of each expenditures category ($i$), $C_{t,i}$ is the average household expenditures by each household type ($t$, by size and income) in the CES, and $C_{\mathrm{usa},i}$ is the average U.S. household consumption, in dollars or physical units. Average U.S. default consumption values, $C_{\mathrm{usa},i}$, for the year 2005 are from the Bureau of Transportation Statistics[22] for transportation (in vehicle miles and passenger miles for public transit modes), the Energy Information Agency[23] for household energy (in physical energy units) at the level of U.S. states, and the Bureau of Economic Analysis (BEA)[24] for food, goods, and services. BEA expenditures on 589 unique products (see the Supporting Information) were then matched with 8 categories of food, 7 categories of goods, and 10 categories of services in the CES. A detailed version of the CES (with ~1500 categories in total) was obtained from the Bureau of Labor Statistics [25] in order to separate goods from services where these categories were combined in the CES summary tables. The consumption-based accounting approach typically assumes that emissions scale linearly with expenditures; however, we scale food-related emissions based on household size (children are assumed to eat 75% of calories of adults), regardless of expenditures on food. We take this approach for two reasons: 1) it is not clear that households that spend more on food necessarily eat more food, and 2) our analysis suggests that the composition of diets is very consistent across income brackets (see the Supporting Information for figures and further data).

In eq 2 above, the CES is used to scale average consumption in each major metropolitan statistical region by average consumption of each household type, by size and income, compared to U.S. average consumption. Location, income, and household size have been reported elsewhere to be the largest determining factors of household environmental impacts.[16,26] The total number of households in the United States in 2005 was roughly 118M, with 2.5 persons per household, on average. Expenditures for income brackets between \$70,000 and \$120,000 were interpolated linearly. Expenditures for cities are for the combined year 2005−2006 for 17 of the 28 cities, and for the next earliest year date are available in the CES for other cities, adjusted to 2005 USD using the Consumer Price Index. The model uses state average electricity and home heating fuel consumption and prices.[21] Correction factors are applied to account for price differences of food, goods, and services in each MSA using the ACCRA Cost of Living Index.[27]

Emission factors are estimated for all 6 greenhouse gases regulated by the Kyoto Protocol, where data are available in the data sets described herein. Gasoline, natural gas, and fuel oil emission factors are from EPA.[28] Argonne National Laboratory's GREET model is used for indirect well-to-pump emissions from gasoline, estimated at 26% of direct emissions. The same indirect emission factor is assumed for fuel oil. Indirect emissions from natural gas are 14% of direct emissions.[26] Emission factors for electricity are from the eGRID database.[29] The boundaries of U.S. states are mapped to individual eGRID subregions, with the exception of New York, which is assumed to be the average of three subregions. Indirect emissions from plant construction and fuel processing are 9% of eGRID emissions.[30]

Emission factors for consumer food, goods, and services are from the Economic Input-Output Life Cycle Assessment (EIO-LCA) model[31] and the Comprehensive Environmental Data Archive (CEDA) model.[32] These input-output models provide estimates of economy-wide cradle-to-gate GHG emissions per dollar of producer output for ~420 sectors of the U.S. economy,[33] of which 289 are relevant to final consumption. While consumers are presented with tens of thousands of individual product choices, each with theoretically distinct emission profiles, input-output models can help consumers distinguish between emissions from large categories of products, such as choosing between chicken or beef,[34] and they are frequently used to approximate aggregate effects of consumption.[14] See the Supporting Information for a discussion of uncertainty associated with input-output analysis as well as steps required to account for emissions from transport and trade margins for 518 products (called "personal consumption expenditures") tabulated by the Bureau of Economic Analysis, and mapping of economic sectors in the EIO-LCA and CEDA data sets to the Consumer Expenditures Survey.

Motor vehicle manufacturing emissions are estimated at 9 $tCO_2e$ per vehicle using EIO-LCA. This estimate is consistent with other published studies.[35−38] Motor vehicle manufacturing emissions are allocated on a per-mile basis, as in other recent studies of transportation emissions.[39,40] Ochoa et al.[41] use EIO-LCA to estimate emissions from U.S. housing construction of new residential 1-unit structures at 110 million $tCO_2e$ in 1997, which equates to 100 tCO2e per home for the 1.1 M single-unit homes completed in that year.[42] Averaging these emissions over a 50-year expected lifetime for the average single-unit home built in 1997 of 2150 square feet[43] results in an annualized emission factor of 930 $gCO_2e$ per square foot. This estimate is higher than other studies,[44−46] which can be expected considering EIO-LCA uses a top-down economy-wide approach. Emissions from water and waste are approximated by multiplying expenditures on "water and other public services" in the CES by an emission factor of 4,121 gCO2e/\$ provided by EIO-LCA for the sector "water and remediation services". A detailed assessment of emissions from water, water treatment, and waste was outside the scope of this study but can be expected to vary considerably from one location to the next.

Upon completion of the carbon footprint calculator, users of the online tool can build scenarios to reduce carbon footprints from different potential actions. For the purposes of this paper, we have selected a single basket of actions, including the following: 1) trading in two 20 mile-per-gallon (mpg) vehicles for 25 mpg vehicles, 2) reducing driving speed and aggressive braking, 3) keeping tires inflated and replacing air filters regularly, 4) telecommuting to work 20 miles per week instead of driving,

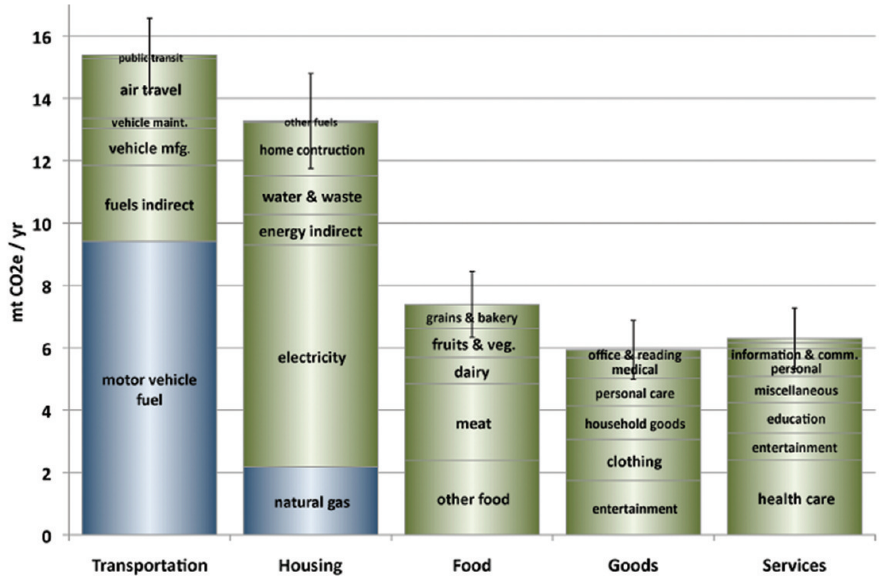


**Figure 1.** Total carbon footprint of the typical U.S. household: 48 t CO2e/yr. Blue indicates direct emissions; green indicates indirect emissions.

5) riding a bicycle 20 miles per week instead of driving, 6) taking public transit 20 miles per week instead of driving, 7) reducing air travel by 20%, 8) turning down the thermostat during winter, 9) turning up the thermostat during summer, 10) drying clothes on the line, 11) replacing five incandescent light bulbs with compact fluorescent light bulbs, 12) choosing an energy-efficient refrigerator, and 13) eating fewer calories, on average, with smaller portions of meat and dairy. Changing thermostat settings can also be interpreted to represent a potentially wide-ranging set of actions to reduce household energy consumption from heating and cooling. Where appropriate, we have accounted for interaction effects, e.g., simultaneously enhancing the fuel efficiency of the household vehicle fleet and reducing vehicle miles traveled. Actions were chosen based on prevalence in the literature[5−7] and the potential for greenhouse gas reductions. Only actions which result in positive net present value (i.e., savings) are considered. The selected actions clearly represent only a subset of total possible actions. Thus, we do not attempt to present an estimate of total potential reductions from behavior change, as other studies have attempted to do,[5,6] but rather seek to demonstrate GHG and financial savings of a set of actions across different geographic and demographic household types. See the Supporting Information for a detailed description of methods, assumptions, and data sources for each action.

## 3. RESULTS AND DISCUSSION

**Carbon Footprint Results and Discussion.** The model produces default carbon footprint results for any combination of 78 regions (50 U.S. states and 28 major metropolitan regions), six household sizes, and 12 income brackets, for a total of over 2000 distinct household types. Figure 1 shows the carbon footprint of the average U.S. household, totaling 48 $tCO_2e$ per year, or roughly 20 $tCO_2e$ per person, for the baseline year of 2005. By comparison, average per capita emissions for the United States (total U.S. GHG inventory divided by the population) are about 24 $tCO_2e$ per person.[47] Emissions from government expenditures are not included in this assessment. Imports are assumed to have the same emissions as U.S. goods and services. Direct emissions (primarily from transportation fuels, natural gas and fuel oil) account for 23% of total emissions, while indirect emissions account for 77%. Direct motor vehicle fuels, 9.4 $tCO_2e$, are the largest contributor to total emissions, followed by electricity: 7.1 $tCO_2e$; meat: 2.5 $tCO_2e$; well-to-pump vehicle fuels: 2.5 $tCO_2e$; healthcare: 2.4 $tCO_2e$; "other food": 2.4 $tCO_2e$;

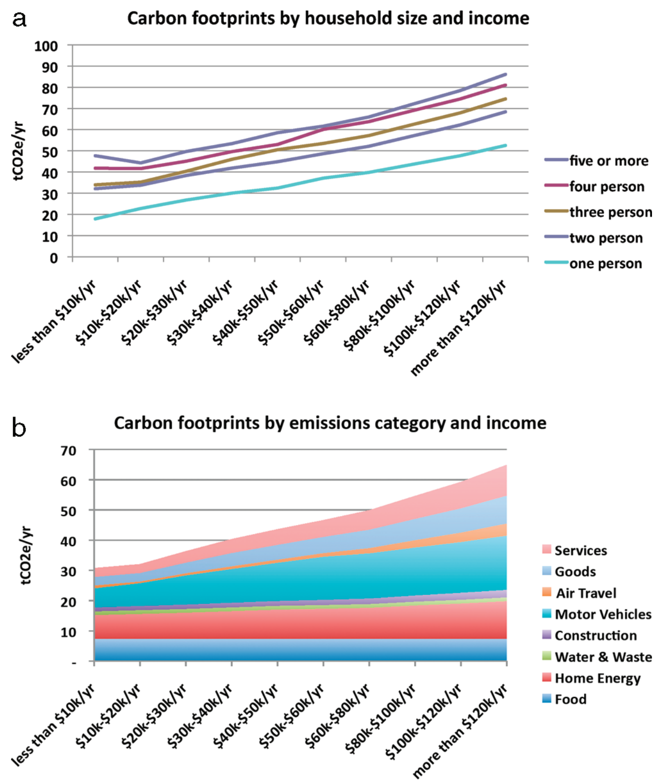


**Figure 2.** (a) Carbon footprints by income bracket and household size. (b) Carbon footprints by category of emissions and income bracket for average household size of 2.5 persons.

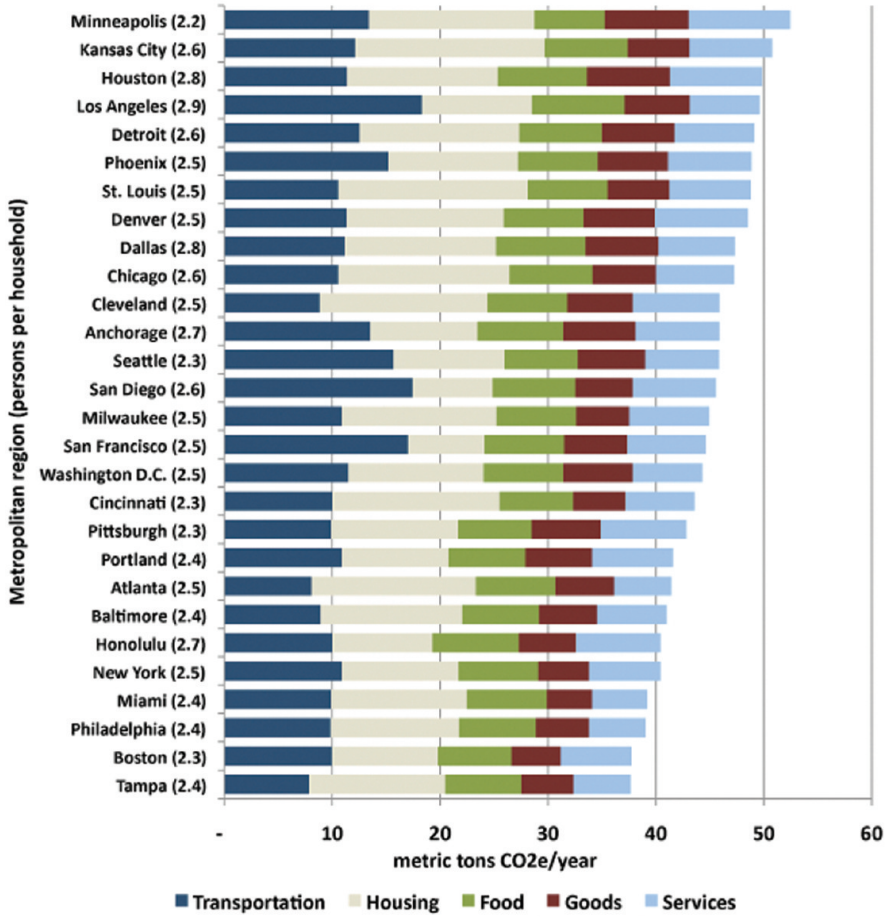


**Figure 3.** Household carbon footprints of the largest (by population) 28 metropolitan regions in the United States. Household size is shown in parentheses to the right of region name. The composition of household carbon footprints is the same as in Figure 1.

natural gas: 2.2 tCO2; and air travel (direct emissions plus indirect effects): ~2 $tCO_2e$.

Uncertainty parameters are calculated based on propagation of standard error estimates for each emission factor. These estimates are largely based on the authors' judgment since published error estimates of emission factors and consumption are rarely available. Uncertainty is estimated at ±1% for fuels but considerably higher (upward of 20%) for indirect emission factors from different data sets. Interested readers can review error estimates in the Supporting Information, Appendix A. Additional user error can also be expected for the online version of the tool.

The size and composition of carbon footprints vary substantially by location, income, and household size. Figure 2 shows average total carbon footprints of households of different sizes and income levels. A three-person household earning $100,000 per year has roughly double the carbon footprint of a three-person household earning $30,000 (60 $tCO_2e$ vs 30 $tCO_2e$). Household size also influences consumption and emissions. A two-person household earning $70,000 emits 52 $tCO_2e$ per year, while a four-person household with the same income emits 64 $tCO_2e$; thus, doubling the number of people per household increases the carbon footprint by 23%, while decreasing per capita emissions by 60%. Increasing household size from two to four adds about another 10 $tCO_2e$ per household, regardless of income level. Two-person households are generally less carbon-intensive than two single-person households on a per capita basis; the combined carbon footprint of two individuals earning $55k per year is about 70 $tCO_2e$ but only 60 $tCO_2e$ for a two-person household earning $110k. Two single-person households have roughly the same carbon footprint as a typical household with two adults and two children.

The composition of carbon footprints also varies considerably (Figure 2), with "housing" comprising 15−30%; transportation: 20−40%; food: 10−30%, between different household types. Carbon footprints of transportation fuel, natural gas, electricity, goods, and services increase predictably with income, with housing displaying low income elasticity, and gasoline consumption increasing substantially as income rises. Food is a small contributor to total carbon footprints (~10%) for single-person households at high incomes but a large category of emissions at low incomes.

The size and composition of carbon footprints varies markedly by location (Figure 3), ranging from 38 $tCO_2e$ in Tampa to 52 $tCO_2e$ in Minneapolis. Transportation footprints range from 8 $tCO_2e$ in Tampa to 18 $tCO_2e$ in Los Angeles. Housing footprints (including direct and indirect emissions from energy, water, waste, and construction) range from 7 $tCO_2e$ in San Francisco to 18 $tCO_2e$ in Kansas City. Emissions from food (5−7 $tCO_2e$), goods (6−8 $tCO_2e$), and services (5−7 $tCO_2e$) are quite consistent between cities. Cities with the lowest carbon footprints tend to have low transportation footprints; however, many cities with low transportation footprints have relatively large

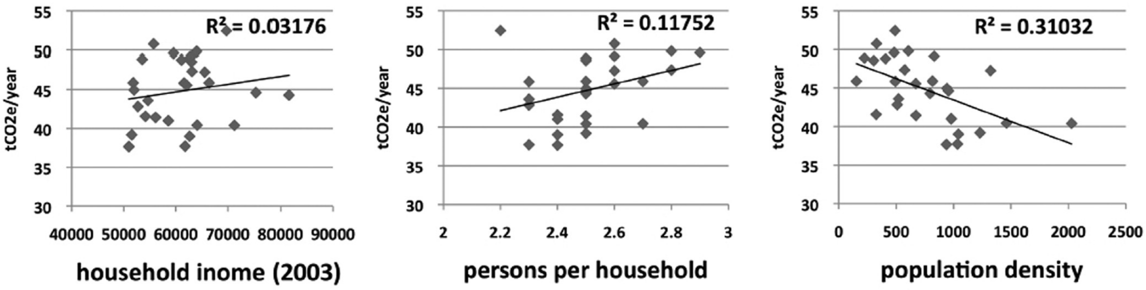


**Figure 4.** Household carbon footprints of U.S. metropolitan regions by household income, persons per household, and population density (persons per square mile of land area).

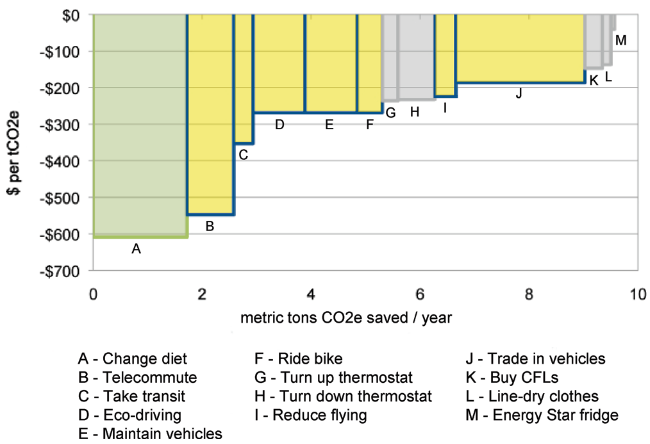


**Figure 5.** Greenhouse Gas (GHG) abatement curve for average U.S. household. *X*-axis is annual GHG savings; *y*-axis is levelized annual cost of mitigation measures per metric ton of $CO_2e$ conserved. Green bars are for changing diets; yellow bars with blue outline are transportation; gray bars are household energy.

housing footprints, e.g., Kansas City, Denver, St. Louis, Cleveland, Cincinnati, and Atlanta. By contrast, San Francisco and San Diego, the two cities with the lowest footprints from household energy (<4 $tCO_2e$ for direct and indirect emissions from electricity, natural gas, other fuels) have large transportation footprints (~17 tCO2e, or nearly 40% of total emissions).

In contrast to differences at the household level, household size and income levels appear to have little effect on total carbon footprints of cities, as shown in Figure 4. While our model linearly scales emissions from food with household size, emissions from transportation, housing, goods, and services show no discernible difference as household size increases. Somewhat surprisingly, Minneapolis, which has the lowest household size (2.2 persons), also has the largest overall carbon footprint (52 tCO2e). Similarly, despite large differences in average annual household incomes (ranging from $51k in Miami to $75k in San Francisco), income has little effect on overall carbon footprints of cities. Several cities with relatively high household incomes have low overall carbon footprints (e.g., New York, Boston, and Baltimore). Higher population density, on the other hand, is strongly correlated with lower carbon footprints (r squared of 0.31), in line with other city carbon footprint studies (e.g., refs 48−50).

**Climate Action Planner Results.** The GHG and financial savings of each individual action are presented in Figure 5 in the form of a greenhouse gas abatement curve[51] with average annual GHG reductions on the *x*-axis and levelized annual cost per metric ton of $CO_2e$ conserved (see the Supporting Information) on the *y*-axis. Under this scenario, the average U.S. household reduces its carbon footprint by 20%, or 9.5 $tCO_2e$ per year, with an upfront cost of $4800, 10-yr net present value of $11,000 (at 8% discount rate and 3% inflation rate), and a payback of 2.6 years. Average financial savings are frequently greater than $100 per metric ton of $CO_2e$ conserved for this set of actions.

Changing diet results in the largest financial savings ($850/yr), largely from lower assumed daily caloric consumption (2200 vs 2500 calories for adults) and price differences between food items. Improving household fleet fuel efficiency by 5 miles per gallon results in 2.5 $tCO_2e$/yr, the largest carbon footprint reduction opportunity modeled. Emission reductions from household energy (1.7 out of 10 tons total) requires a larger number of individual actions to achieve GHG reductions, although some of these are one-time actions, such as replacing light bulbs and choosing an Energy Star refrigerator, which are arguably easier to implement than actions that require daily changes in behavior.

Presenting carbon footprints and climate action plan results for each of the >2000 household types in the model is not possible for this paper; however, Figure 6 presents results for two hypothetical households for illustration purposes. Household A is a 2-person household earning $90,000 per year, living in the San Francisco Bay Area. Household B is a 5-person household with $45,000 annual income, living in St. Louis. Climate action plan results to achieve a 20% GHG reduction are presented for each household.

The Carbon footprint of household A is dominated by emissions from motor vehicles and air travel. Emissions from household energy are about half of the U.S. average due largely to the relatively clean fuel mix of California's electricity grid and moderate San Francisco Bay Area climate. The household has essentially no emissions from cooling. Emissions from goods and services outstrip emissions from food due to the household's relatively high income and low number of household members. The total ~20% footprint reduction potential modeled corresponds to about $2100/yr in potential financial savings. As could be expected, transportation dominates total carbon footprint reduction potential (8 out of 10 $tCO_2e$/yr total).

The carbon footprint of household B is dominated by emissions from electricity. This is largely a product of high emissions per kWh of electricity in St. Louis and larger than average heating and cooling demands. Emissions from food also outstrip direct and indirect emissions from motor vehicles, due to the large household size. This modest income family has lower

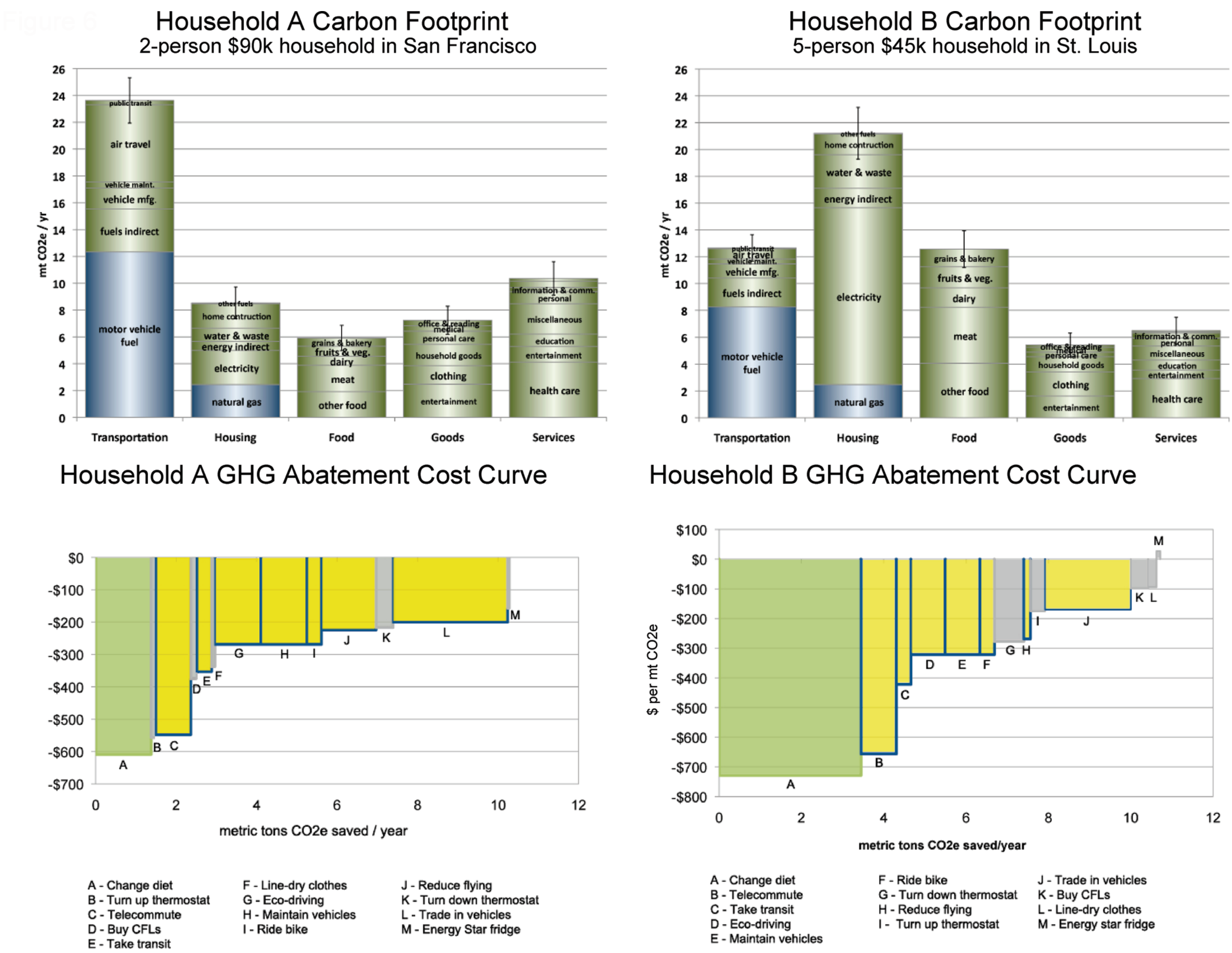


**Figure 6.** Carbon footprints and GHG abatement cost curves for example households. Household A is an upper income two-person household in the San Francisco Bay Area. Household B is a middle-income five-person household in St. Louis. In the upper figures, carbon footprints are shown for the major categories of emissions, with annual $CO_2e$ emissions on the *y*-axis. In the lower figures, *X*-axis is annual GHG savings; *y*-axis is levelized annual cost of mitigation measures per metric ton of $CO_2e$ conserved. Green bars are for changing diets; yellow bars with blue outline are transportation; solid gray bars are household energy.

than average emissions from goods and services. The household can save $1400 per year and reduce its carbon footprint by almost 3 $tCO_2e/yr$ by reducing overeating and waste from food and reducing the amount of meat, dairy, and nonessential food items consumed. Further savings of $500 per year and 3 $tCO_2e/yr$ can be obtained by increasing the family's average fuel efficiency from 20 mpg to 25 mpg, reducing total vehicle miles traveled and practicing fuel-saving driving and vehicle maintenance habits. The household has virtually no emissions from air travel. Carbon footprint savings of 2 $tCO_2e$ can be achieved by adjusting the thermostat, replacing light bulbs, and line-drying clothes; however, financial savings are less than $200/yr due to relatively low energy prices in the state of Missouri.

**Discussion of Climate Action Planner Results.** Example households A and B demonstrate the utility of tailoring different carbon reduction policies and programs to different audiences based on the size and composition of household carbon footprints. For the typical two-person San Francisco household earning $90,000 per year, transportation carbon footprints outstrip household energy (electricity, natural gas, and other fuels) by more than five to one. For a typical five-person household in St. Louis, on the other hand, emissions from household energy are 1.5 times greater than emissions from transportation. While these represent rather extreme cases, Figures 2a,b and 3 demonstrate that the composition of carbon footprints can vary quite dramatically between different population segments, suggesting that one-size-fits-all messages, policies, and programs may be shortsighted and less effective than more targeted messages and programs.

At the same time, assessing the actual potential for households to engage in lower-GHG lifestyles requires an understanding of the barriers preventing individuals from taking particular actions.[2] For example, household B has roughly an equal opportunity to reduce emissions from transportation, household energy, and food. Increasing vehicle fuel efficiency may be attractive for the financial savings, although some families may perceive smaller, more fuel-efficient vehicles as being less safe. Reducing highway speed and aggressive driving, on the other hand, increases both safety and fuel efficiency. Saving household energy may also not be particularly appealing on financial grounds given the state's low energy prices (the high carbon footprint of electricity may be more effectively addressed through policies to reduce the carbon-intensity of electricity production, and potentially raising prices on energy). Programs targeted at encouraging low-carbon and healthy dietary choices, on the other hand, may hold potential for this household type. Reducing the households' food carbon footprint may be only a side benefit compared to the health benefits of reducing obesity, which is particularly prevalent in some lower income regions.[52]

The upper income 2-person household in California (household A) presents a very different set of mitigation opportunities. Similar to Household B, the carbon footprint of this household is about 20% higher than the U.S. average (and 6 times the global average); however, the carbon footprint is dominated by transportation, both from motor vehicles and air travel. The total financial savings of $2100 per year are much less of an incentive for higher income household, particularly if these savings involve a large number of actions that may take considerable time and effort. Improving the household's average fuel efficiency from 20 to 25 mpg presents an attractive opportunity from a carbon footprint standpoint, saving 2.5 $tCO_2e$/yr. While the $225/yr in fuel savings may not be a large incentive, in environmentally conscious California clean cars can project higher social status, providing an important social incentive to drive fuel-efficient vehicles. Reducing air travel, or possibly purchasing carbon offsets, is an important aspect of this household's carbon footprint mitigation potential. While emissions from food are small relative to other emissions, focusing on the health and environmental benefits of vegetarian diets may be attractive as a social marketing technique in this geographic region and demographic.

While carbon footprint and GHG abatement opportunities vary greatly from one household type to the next, substantial GHG savings opportunities are possible across all geographic areas and demographic types modeled if behavior changes and energy efficient technologies are adopted. Financial and GHG savings potential from transportation are large across all household types; savings potential from diet switching depend largely on household size, and savings from housing depend largely on the price and GHG-intensity of household fuels, and energy consumption rates in different climate zones.

While consumption-based carbon calculators are a relatively new concept, we suggest that they can be valuable to reduce consumption-related greenhouse gas emissions by 1) encouraging a larger range of individual and household behavior changes, 2) reducing rebound effects and other unintended consequences associated with a more limited view of consumer responsibility, 3) allowing individuals to benchmark their emission profiles with similar households, global averages and sustainable levels, 4) encouraging development of community action, 5) encouraging internalization of external costs related to greenhouse gas emissions and subsequently funding carbon mitigation projects, and 6) sending market signals to producers of goods and services to reduce supply chain and full life cycle emissions. Information campaigns alone have historically been noted to have had limited impact on changing consumer behavior;[4] indeed most policies are directed not at individuals but at community-scales, such as encouraging urban infill to increase population density. Nonetheless, large differences exist between cities with similar population densities and other characteristics, implying that information may play some role in affecting attitudes, norms, habits, and other determinants of behavior.[53,54]

Sustainable consumption has been called both the "next wave"[55,56] and the "holy grail"[57] of environmental policy, highlighting both the enthusiasm for and the difficulty of actually implementing effective sustainable consumption programs and policies. At the same time, learning how to balance economic growth with environmental concerns is arguably the fundamental objective of sustainable development. Individuals can not learn to live more sustainably if they do not have information to help them make more environmentally benign decisions. Carbon footprint calculators are one mechanism to help consumers become aware of their impact on the planet and to target behaviors to reduce this impact over time. If carefully constructed, these tools may help realize some of promise and enthusiasm for sustainable consumption programs and policies.

## ■ ASSOCIATED CONTENT

**Supporting Information.** 1) Detailed description of methods for the household carbon footprint model, 2) a detailed description of methods for each action, and 3) a list of emission factors with approximated uncertainty bounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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## ■ NOTE ADDED AFTER ASAP PUBLICATION

Figures 5 and 6 were incorrect in the version of this paper published March 30, 2011. The correct version published April 11, 2011.