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Comparing the relative mitigation potential of individual pro-environmental behaviors

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ABSTRACT

Anthropogenic greenhouse gas emissions are modifying climate patterns on a global scale. Behavior changes at the household level can help limit the magnitude of carbon emissions and associated climate change. The objective of this study is to determine which individual actions have the largest potential for reducing household greenhouse gas emissions. Past behavior change research has focused on the reduction potential of direct emissions in one or two household domains at a time, often overlooking the indirect emissions associated with food consumption. Here, the potential greenhouse gas emissions reductions are compared for seven individual pro-environmental behaviors in the transportation, housing, and food domains. For the average household in North America and Europe, eating fewer animal products has the largest greenhouse gas emissions reduction potential of the behaviors studied, followed by switching to more fuel-efficient vehicles. Additional analyses reveal that air transportation might have larger emission reduction potential than dietary changes, especially for higher-income households that fly frequently. Targeting these high-impact behaviors will be more cost-beneficial for climate change policies and programs. This study can help guide these intervention efforts.

1. Introduction

Climate change is threatening human health, ecosystem health, and economic activity on a global scale (Intergovernmental Panel on Climate Change, 2014a). Many researchers agree that behavioral changes are necessary to address this problem, and that individual actions at the household level have great mitigation potential (e.g., Dietz et al., 2009; Intergovernmental Panel on Climate Change, 2014b; Schultz and Kaiser, 2012; Swim et al., 2009). For example, direct energy use by households in the United States is responsible for 38% of national greenhouse gas (GHG) emissions, and 8% of global GHG emissions (Dietz et al., 2009; Gardner and Stern, 2008).

Recognizing the mitigation potential associated with behavior change, environmental psychologists have dedicated efforts to studying the predictors of pro-environmental behavior (PEB) in a wide variety of domains, ranging from energy (Abrahamse and Steg, 2011), to transportation (Bamberg and Schmidt, 2003), to food (Graça et al., 2015). While they found that values, social norms, and attitudes tend to positively correlate with PEB, to name a few, psychological barriers limit the uptake of climate-positive behavior (Blake, 1999; Stoll-Kleemann, O'Riordan and Jaeger, 2001; Lorenzoni et al., 2007; Takacs-Santa, 2007; Patchen, 2010; Gifford, 2011).

One important psychological barrier is the single-action bias or the tokenism barrier (Gifford, 2011; Weber, 2010). The single-action bias is the tendency for individuals to do only one action when responding to a threat (Weber, 2010). Similarly, tokenism is the belief that one is already doing enough environmental actions (Gifford, 2011). Recent research has demonstrated that this tokenism barrier applies to climate-positive food choices (Gifford and Chen, 2017). In addition, after behaving pro-environmentally, one may feel they have acquired a moral license to subsequently behave in an environmentally-harmful manner (Huddart Kennedy et al., 2009; Nolan and Schultz, 2015). Even with good environmental intentions, individuals often pick the easier changes, and not necessarily the ones with the most environmental impact (Huddart Kennedy et al., 2009; Stern, 2000; Gifford, 2011, 2013; Schultz and Kaiser, 2012).

1.1. Past research and study objectives

Past studies provide comparisons between the GHG emissions

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associated with multiple environmental domains (Druckman et al., 2011; Ferguson and MacLean, 2011; Frostell et al., 2015; Jones and Kammen, 2011; Miehe et al., 2016; Tukker et al., 2006; Weber and Matthews, 2008). Tukker et al. (2006) review the life cycle environmental impacts of product consumption in the European Union and conclude that food, transportation, and energy are the most impactful domains. However, these past studies do not provide insight on the impacts of individual behaviors within each domain.

Dietz et al. (2009) provide an analysis of the behavior-specific emissions associated with household energy-use (e.g., home heating and transportation). Through a combination of 17 behavior changes in the housing and transportation domains, American households can reduce national GHG emissions by 7.4% (Dietz et al., 2009). Some impactful behaviors include switching to more fuel-efficient vehicles, weatherization (e.g., insulation), and buying energy-efficient appliances. However, Dietz et al. (2009) do not consider household indirect emissions, which are often larger than their direct emissions (Steg and Abrahamse, 2010; Swim et al., 2012).

Indirect emissions such as those related to food choices have important emission reduction potential (Stern, 2011). Past studies have comprehensively researched the potential impact of food choices (Hallström et al., 2015; Aleksandrowicz et al., 2016). However, they do not compare the impact of dietary changes to behaviors from other domains, for example, the potential GHG reductions associated with driving a more fuel-efficient car.

One study compares the mitigation potential of 13 household direct (e.g., using public transportation instead of driving) and indirect (i.e., dietary change) PEBs (Jones and Kammen, 2011). Although it provides a good starting point for this analysis, its application is limited to the United States and their model does not account for varying degrees of behavior change (e.g., only a small reduction in meat and dairy consumption is modelled).

Recognizing that individuals tend to engage in few (low-impact) PEBs, researchers aiming to help mitigate climate change through behavior change should focus their efforts on those behaviors that have significant potential for reducing greenhouse gas (GHG) emissions. The objective of this study is to determine which individual actions have the largest potential for reducing an individual's carbon footprint in high-income countries. Whereas independently none of the previous studies meet the study objective, the approach used here allows to combine their findings and quantify the relative mitigation potential of individual PEBs.

2. Methods

In the literature, the mitigation potential of single behaviors is rarely, if ever, expressed as a portion of an individual's total GHG emissions. Instead, it is usually expressed as a portion of a specific domain's GHG emissions (e.g., food-related GHG; Berners-Lee et al., 2012). To compare the mitigation potential of behaviors from different domains, these data must be converted into analogous values, in this case, a behavior's mitigation potential relative to the total footprint of the average individual.

A systematic review was conducted to gather baseline emissions data, focusing on high-income countries (also commonly referred to in the literature as western nations or developed countries). High-income countries were chosen because they have the largest per capita climate change impact. Then, the range of achievable GHG emissions reductions for each behavior relative to the average individual's total GHG emissions was calculated. More specifically, these were the steps followed:

1) Review the existing literature and gather baseline data for the average carbon footprint by domain (i.e., the GHG "piece of pie" for food, transportation, housing, etc.).
2) Review the existing literature and gather comparative data for the carbon footprint of behaviors.
3) Using the baseline data gathered during steps 1 and 2, calculate the range of achievable GHG emissions reductions for each behavior expressed as a portion of the average individual's total GHG emissions (see section 2.2 for formulas).

2.1. Key terms

Some of the terms used in this study warrant definition. Building from the concept of environmentally-significant behavior, defined as any behavior that "changes the availability of materials or energy from the environment or alters the structure and dynamics of ecosystems or the biosphere itself" (Stern, 2000, p. 408), pro-environmental behavior is any behavior that aims to reduce the harmful impacts of environmentally-significant behavior (e.g., resource conservation; Gardner and Stern, 2008; Nolan and Schultz, 2015).

More specifically, this study focuses on single PEBs (e.g., thermostat setback) aiming to reduce GHG emissions (e.g., carbon dioxide, methane, nitrous oxide), as opposed to a combination of behaviors or product groupings (e.g., an aggregate of energy reduction behaviors like switching off lights, unplugging chargers, etc.). The term carbon footprint includes emissions from all GHGs, usually expressed in units of carbon dioxide equivalent (e.g., Jones and Kammen, 2011).

A behavioral domain is defined as the functional area of consumption, at the highest level of product category aggregation (Tukker et al., 2006). Domains are commonly grouped under the functional areas of transportation, food, energy, waste disposal, and material purchases (Gifford, 2014).

The *absolute* carbon footprint is defined as the total GHG emissions associated with a behavior or a domain (specified accordingly) per year for the average individual, expressed in a unit (e.g., tonnes) of carbon dioxide equivalent emissions. The *relative* carbon footprint of a domain specifies the portion of GHG emissions associated with a domain relative to the average individual's total yearly footprint, expressed as a percentage. The *relative* carbon footprint of a behavior specifies the portion of GHG emissions reductions associated with a behavior change as a portion of the *domain* footprint.

Recognizing that the relative footprint of each domain or behavior varies (see section 2.4), the relative footprints obtained will represent a range, with low- and high-points. The *range of achievable GHG emissions reductions* is defined as the potential GHG emissions reductions associated with a behavior, expressed as a portion of the average individual's total carbon footprint. Unlike the relative footprint of a behavior, the range of achievable GHG emissions reductions also considers the footprint of each domain relative to the total. Ultimately, comparing the ranges of achievable GHG emissions reductions for each behavior will help determine which individual actions have the largest mitigation potential.

2.2. Formulas

The focus of this study is on carbon footprints of specific behaviors relative to the average individual's total carbon footprint. Each domain's *relative* footprint depends on the sum (*total footprint*) of the *absolute* footprints in all domains.

The relative carbon footprint of each domain will be calculated as follows:

$$\mathrm{Dom_i} = \mathrm{A_i}/\mathrm{T}$$

where Dom_i is the relative footprint of a domain i (food, transportation, etc.), A_i is the absolute footprint of that domain i, and T is the total footprint. This formula is repeated across multiple domains.

However, the absolute footprints (per domain and total) vary slightly between households based on their income, region, and household types (e.g., Jones and Kammen, 2014; more information in section 2.4). For this reason, it was deemed preferable to use a *range* of domain footprints (e.g., food is 10%–30% of total household GHG) to get a better estimate. This approach is repeated across multiple studies and these multiple data sources are combined to calculate the low- and high-points of the relative footprints for each domain.

Unless already reported in the literature (e.g., median reductions associated with eating less meat is 22% of food-related GHG; Aleksandrowicz et al., 2016), the relative carbon footprint by behavior will be calculated as follows:

$$\mathrm{Beh_i} = \mathrm{B_i}/\mathrm{A}$$

where Beh_i is the domain relative carbon footprint reductions by behavior i (e.g., buying a fuel-efficient car), B_i is the absolute reduction potential of that behavior i, expressed in a unit of GHG emissions reduction, and A is the absolute footprint of that domain. This is repeated across multiple studies to gather best estimates.

The estimated range of achievable emissions reductions will vary based on the domain's portion of the total footprint (i.e., *relative* domain footprint or Dom_i), and on the degree of behavior change expressed in each study (i.e., small reduction in meat consumption vs. vegetarian). The range of achievable emissions reductions for each behavior will be calculated as follows:

$$\mathrm{Ach_i} = \mathrm{Dom_i} \times \mathrm{Beh_i}$$

where Ach_i is the achievable emissions reductions for a specific behavior (e.g., eating animal products, fuel-efficient car, etc.), Dom_i is the relative footprint of that domain, and Beh_i is the behavior footprint relative to the domain. A low-level and high-level of achievable emissions reductions will be calculated, using the low- and high-range of relative footprints by domain and by behavior across studies.

The following example illustrates how the range of achievable GHG emissions reductions for each behavior is obtained: (1) If the average individual's food carbon footprint is 10–30% of their total carbon footprint (i.e., Dom_i), and (2) if eating fewer animal products (i.e., Beh_i), has a potential reduction of up to 35% of *food-related* GHG for a vegetarian diet and up to 55% for a vegan diet (Hallström et al., 2015), then (3) we can calculate the range of achievable GHG emissions reductions associated with a switch to a vegetarian or vegan diet (i.e., $Ach_i = Dom_i \; X \; Beh_i$).

In this example, the range of achievable emissions reduction is between 3.5% and 16.3% of the average individual's total carbon footprint, calculated as follows:

a Low-range value (i.e., 3.5%) is based on the lowest-range of the food domain (Dom_i) estimated at 10% of the total footprint, and the low-range behavior (Beh_i) estimated at 35% reduction of food-related GHG ($Ach_i = 0.10 * 0.35$).
b High-range value (i.e., 16.3%) is calculated based on the highest-range of the food domain (Dom_i) estimated at 30% of the total footprint, and the high-range behavior (Beh_i) at 55% reduction of food-related GHG ($Ach_i = 0.30 * 0.55$).

2.3. Database search and criteria

Based on the study objectives, it was decided that only studies comparing GHG emissions across two or more domains (e.g., food, transportation, housing) would be included to calculate the average footprint for each domain. Using only these studies controls for some of the variance in model assumptions (see section 2.5), thus allowing to optimise the comparability between studies. For the domain footprint search, the keywords (carbon OR greenhouse gas OR footprint) AND (estimate* OR quantif* OR model*) AND (individual OR household) were entered in the Web of Science database.

The following types of studies were frequently found and excluded based on the scope of the study: studies that take place outside of high-income countries, policy studies (e.g., carbon tax), studies focusing on non-household footprints (e.g., industry), and studies focusing exclusively on one domain (e.g., agriculture and cattle feed). The keyword "carbon" often retrieved some unrelated articles (e.g., carbon nanotubes), and those were excluded as well.

For the domain footprint keyword search, 326 results were found, 16 of which were within the scope of the study. After more careful examination, 9 were excluded because they only included a limited number of domains (e.g., only energy use). In the end, seven articles were retained from the database search. One of these (i.e.,Tukker and Jansen, 2006) was replaced by the original study (i.e., Tukker et al., 2006) for more detailed data.

Studies needed to compare the GHG emissions of multiple behaviors (i.e., minimum five) in more than one domain to be included as comparative data for the carbon footprint of behaviors. For this search, the keywords (carbon OR greenhouse gas OR footprint) AND (change OR mitigat* OR reduc*) AND (individual OR household) were entered in the Web of Science database. Exclusion criteria were similar to the above description.

Because this study uses existing data as its baseline, it is inevitably guided or limited by the current literature. It was decided prior to conducting the database search that if the same PEBs were regularly included in comparative studies, these would become the behaviors of focus for the present study. A minimum of three sources for each behavior should be used to calculate a reliable range of achievable GHG emissions reductions.

Only two peer-reviewed articles met the inclusion criteria for the potential emissions reduction by behavior search. Governmental websites were consulted to complement the research findings, following the same inclusion criteria. One European Commission report, made-up of multiple domain-specific reports, was located. This allowed to narrow down the scope of the study to six behaviors that were most frequently included in comparative studies.

For three (i.e., line-drying, teleworking, eating fewer animal products) out of six behaviors, the initial search did not meet the pre-established minimum number of sources, and thus specific keywords searches were conducted to target literature estimating their GHG emissions (e.g., (carbon OR greenhouse gas OR environment* OR ecology*) AND (change OR mitigat* OR reduc* OR emissions) AND (meat OR veg* OR diet* OR food)). A recent comprehensive meta-analysis reviewing 63 studies on the potential impact of dietary changes was located (Aleksandrowicz et al., 2016). However, there were no additional studies assessing the GHG emissions reductions on a household or individual level for line-drying clothes and teleworking, thus only two sources are reported for these behaviors. In the end, two peer-reviewed articles comparing multiple behaviors, one governmental source, and one behavior specific (i.e., eating less animal products) meta-analysis were included.

2.4. Domains and behaviors defined

The categories and sub-categories that comprise each domain vary between studies (e.g., sometimes housing includes electricity, other times it is excluded). After careful consideration and when necessary, some categories were re-grouped to ensure that the domains were comparable across studies (detailed in Table 1). The food domain includes GHG emissions from food, alcohol, and tobacco consumed. The food domain excludes emissions from restaurants.

The transportation domain includes emissions from personal vehicle fuels and other fuels associated with transportation. Air transportation is likely underrepresented in this domain; three studies (Jones and Kammen, 2011, 2011; Frostell et al., 2015; Miehe et al., 2016) include air transportation, three do not specify (Weber and Matthews, 2008; Druckman et al., 2011; Ferguson and MacLean, 2011), and one (Tukker et al., 2006) includes it but warns readers that it is not adequately quantified because of methodological challenges.

The housing domain generally includes emissions from electricity, natural gas (and other non-transportation fuels), water, waste, emissions from the production of appliances and household equipment, and maintenance.

Behaviors that were consistently included in comparative studies were retained (i.e., eating fewer animal products, fuel-efficient vehicles, eco-driving, teleworking, thermostat setbacks, and line-drying clothes). However, slight variations in behavior definitions exist between studies, as described in the following paragraphs. These are reflected in the resulting emissions reductions potentials.

Within the food domain, eating fewer animal products (i.e., meat, fish, dairy, eggs) can reduce an individual's carbon footprint indirectly through reduced waste and input needed (e.g., land-use, feed, water, gasoline) per output of food produced (Sabaté et al.,

Table 1
Absolute and relative carbon footprints of each domain.

Study	Miehe et al., 2016	Frostell et al., 2015	Jones and Kammen, 2011	Druckman et al., 2011	Ferguson and MacLean, 2011	Weber and Matthews, 2008	Tukker et al., 2006
Region	Germany, average household	Sweden, average household	United States, average household	United Kingdom, average household	Canada, household per capita	United States, household	25 member states of the EU, total expenditure
Data source	German Statistical Bureau and National food consumption studies	Statistics Sweden database	Multiple sources (e.g., Bureau of Transportation Statistics, EPA, eGRID database, Economic Input-Output Life Cycle Assessment model, etc.)	Models used to estimate GHG emissions and household expenditure, populated by UK governmental data	Data from national surveys, personal consumption expenditure (year 1997)	Consumer expenditure surveys	Literature review
Model	Multi-region input-output model	Hybrid model, national input-output analysis and life cycle inventory analysis	Economic input-output life cycle assessment model and comprehensive environmental data archive model	Input-output model. Includes direct energy use and embedded emissions	Economic input-output LCA model	Life cycle assessment techniques	Input-output analysis
Domains	5 categories, 29 sub-categories Grouped as: Food, Transportation, Housing, Goods, Services	4 categories, 21 sub-categories Grouped as: Food (combined food and alcohol), Transport, Housing (home and living)	5 categories, 27 sub-categories Grouped as: Food, Transportation, Housing (including household goods), Goods (excluding household goods), Services	8 categories, 17 sub-categories Grouped as: Food, Transportation (combined vehicle fuels and other transport), Housing (combined electricity, gas, other fuels, housing, furniture)	29 sub- categories Grouped as: Food, Transportation, Housing (combined household and shelter)	13 categories Grouped as: Food (combined food and alcohol), Transport, Housing (combined housing, furnishing and home energy)	12 categories Re-grouped: Food (combined food and alcohol), Transportation, Housing (combined housing, water, electricity, gas, furnishings, maintenance)
GHG Unit	Tons CO_2 equivalent/yr	Kilograms CO_2 equivalent/yr	Metric ton CO_2 equivalent/yr	Tonnes CO_2e (or Metric ton)/yr	Kilograms CO_2 equivalent/yr	Metric ton CO_2/yr	% of total yearly expenditure in the EU-25
Absolute footprint of each domain	Data extracted from Fig. 2 in Miehe et al (2016). Transportation: 7.08 tCO_2e Food: 5.51 tCO_2e Housing: 10.12 tCO_2e Other: 7.29 tCO_2e *Total: 30 t CO_2e*	Data extracted from Fig. 6 in Frostell et al (2015). Transportation: 2.07 kg CO_2e Food: 1.99 kg CO_2e Housing: 1.21 kg CO_2e Other: 1.79 kg CO_2e *Total: 7.06 kg CO_2e*	Data extracted from Fig. 1 in Jones and Kammen (2011). Transportation: 15.4 $MtCO_2e$ Food: 7.5 $MtCO_2e$ Housing: 14.4 $MtCO_2e$ *Total: 48 Mt CO_2e*	Data extracted from Fig. 1(b) *corrigendum* in Druckman et al (2011). Food: 3.61 tCO_2e Transportation: 7.43 tCO_2e Housing: 9.98 tCO_2e Other: 7.43 tCO_2e *Total: 28.58 t CO_2e*	Data extracted from Table 2 in Ferguson and MacLean (2011). Transport: 3533 kg CO_2e Housing: 4123 kg CO_2e Food: 2293 kg CO_2e *Total: 11,123 Kg CO_2e*	Data extracted from Fig. 1 in Weber and Matthews (2008). Food: 550 Mt CO_2 Housing: 1910 Mt CO_2 Transport: 1635 Mt CO_2 *Total: 5835 Mt CO_2*	Data extracted from Table 5.4.4 in Tukker et al (2006). *(relative footprint of each domain provided, see below)*
Relative footprint of each domain (i.e., as % of the total footprint)	$Dom_i = A_i/T$ Transport: 23.6% Food: 18.4% Housing: 33.4%	$Dom_i = A_i/T$ Transport: 29.4% Food: 28.1% Housing: 17.1%	$Dom_i = A_i/T$ Transport: 31.8% Food: 15.1% Housing: 30%	$Dom_i = A_i/T$ Transport: 26.5% Food: 12.6% Housing: 34.9%	$Dom_i = A_i/T$ Transport: 31.8% Food: 20.6% Housing: 37.1%	$Dom_i = A_{ii}/T$ Transport: 28% Food: 9.4% Housing: 32.7%	Transport: 18.5% Food: 31% Housing: 23.6%

2014). Most studies use the average diet as the starting point for modelling the potential carbon footprint reductions of eating fewer animal products. However, the dietary change modelled varies substantially between studies, from small changes (e.g., beef partially replaced by dairy products) to very large changes (e.g., veganism). Jones and Kammen (2011) define dietary change as "eating fewer calories, on average, with smaller portions of meat and dairy" (p. 4090). Studies from the European Commission (Faber et al., 2012a, b; Köhler and Köhler, 2012) present a range of dietary options, from a small (one meatless day per week) to a large (vegetarian diet) degree of change. The meta-analysis (Aleksandrowicz et al., 2016) presents the widest and most comprehensive variety of dietary options, from partially replacing meat by dairy products to veganism.

Within the transportation domain, switching to a more fuel-efficient vehicle can reduce the use of gasoline and associated carbon emissions. This behavior is defined as switching from a conventional car to a more fuel-efficient car. The fuel-efficiency criteria for conventional and fuel-efficient cars vary between studies. Dietz et al. (2009) apply the most stringent fuel-efficiency criteria (i.e., replace a 20.8 mpg car with 30.7 mpg), followed by Jones and Kammen (2011; 20 mpg replaced with 25 mpg, replace two cars), and the European Commission studies (Schroten, 2012; smaller car using 17–20% less gas per kilometre). This behavior does not include hybrid or plug-in electric vehicles.

Within the transportation domain, improved driving style can reduce the amount of gasoline consumed and associated GHG emissions. Eco-driving refers to the practice of adopting a more fuel-efficient driving style. Most studies define this as a combination of reducing aggressive driving (rate of acceleration and braking), speed, and idling. To avoid double-counting, studies accounted for interaction effects between eco-driving and switching to more fuel-efficient cars.

Within the transportation domain, teleworking can reduce the amount of gasoline used by reducing the number of trips to the office each week. Teleworking is defined as working from home one-day per week in both studies (European Commission studies, 2012; Jones and Kammen, 2011). The European Commission studies (Faber et al., 2012a,b; Köhler and Köhler, 2012; Schroten, 2012) consider rebound effects (e.g., energy-use for home heating) and attempt to estimate the maximum number of individuals in the workforce who are able to telework.

Within the housing domain, thermostat setbacks can reduce energy-use associated with space heating and cooling. Thermostat setbacks refer to either decreasing the temperature setting in winter, or increasing the temperature setting in the summer (i.e., using less air conditioning). The specific definitions vary between studies. Dietz et al. (2009) specify a 4–7 °F reduction in the winter, depending on the time of day and occupancy, and a 5–7 °F increase in the summer. Jones and Kammen (2011) define this behavior as a 2–8 °F reduction in the winter, and a 5–7 °F increase in the summer. The European Commission studies (Faber et al., 2012a,b; Köhler and Köhler, 2012; Rohde et al., 2012) provide two scenarios; a 1 °C reduction or a 2 °C reduction.

Within the housing domain, line-drying clothes (i.e., air drying) can reduce electricity use associated with operating a drying machine. The criteria for line-drying vary significantly; Dietz et al. (2009) specify line-drying 5-months out of the year, whereas Jones and Kammen (2011) specify line-drying for 130 loads of laundry per year.

2.5. Assumptions

Some assumptions apply to this study. Carbon footprint averages are used to obtain best estimates of PEB impacts; nevertheless, there is variation between individuals' carbon footprints. For example, research demonstrates variations in energy domain footprints based on regional climate and on the sources of electricity (Jones and Kammen, 2014). Furthermore, in general, urban households have smaller carbon footprints than suburban ones (Tukker et al., 2010; Jones and Kammen, 2014; Holian and Kahn, 2015), and smaller households (i.e., fewer people per household) have larger per capita carbon footprints than larger households (Tukker et al., 2010; Zhang et al., 2015).

Low-income households tend to have smaller carbon footprints than high-income households, but different domains have different elasticities, relative to the changes in income level (Isaksen and Narbel, 2017). The carbon footprints from energy and food are less susceptible to changes in income than the transport footprint; a 1% increase in income leads to a 0.3% increase in energy emissions, a 0.5% increase in food emissions, and a 1% increase in transport emissions (Jones and Kammen, 2011; Isaksen and Narbel, 2017). Despite these variations between individuals, using averages and low- and high-ranges of carbon footprints as best estimates will allow to meet the study's objective by comparing the achievable emissions reductions of different behaviors.

Carbon footprint estimates also vary depending on the quantification model used (e.g., input-output model, life cycle assessment, emission coefficient). This review included consumption-based models, which typically consider direct and indirect carbon emissions related to household consumption (Zhang et al., 2015). Imported products consumed inside each country are thus included in consumption-based models. However, some models assume that the imported products consumed inside the country have the same footprint as those produced nationally (Jones and Kammen, 2011), and others use emissions data specific to the producing country (Miehe et al., 2016). Some models consider rebound effects, while some attempt to give a realistic estimate based on behavior plasticity, and others present the maximum potential emissions. For a detailed overview of each model's assumptions, advantages and disadvantages, see Zhang et al. (2015). For the present study, the models used in the cited research are detailed in Tables 1 and 2.

3. Results

Seven studies comparing the absolute carbon footprints of different domains were retained. For each study, the study region, data source, quantification model used, and absolute carbon footprint of each domain is detailed in Table 1. Furthermore, Table 1 includes detailed calculations of the relative footprint associated with each domain.

Four studies comparing achievable GHG emission reductions for multiple PEBs were retained. For each study, the study region, data source, quantification model used, and included PEBs are detailed in Table 2. Also, the potential GHG emission reductions for each behavior are expressed in absolute and relative terms along with the applicable formulas.

3.1. Carbon footprints for each domain

Applying the relative carbon footprint by domain formula to each study (i.e., $Dom_i = A_i/T$) reveals that the relative carbon footprints of each domain fluctuates slightly between countries (Table 1). Generally, relative footprint estimates for the transportation domain are lower for studies conducted in Europe, compared to Canada and the United States. On the other hand, relative domain footprint estimates for food are lower for studies conducted in Canada and the United States. This highlights the *relativity* of these data and the interactions between domains; a larger absolute footprint for the transportation domain will

Table 2
Achievable GHG emissions reductions for each behavior.

Study	Dietz et al., 2009	Jones and Kammen, 2011	European Commission, 2012[a]	Aleksandrowicz et al., 2016
Region	United States	United States	European Union	High-income countries (e.g., US, Canada, Netherlands, UK)
Data source	Data from the literature (e.g., Gardner and Stern, 2008; Vandenberg et al., 2008)	Data for consumption levels from governmental sources (e.g., Bureau of Transportation Statistics, etc.) Data for emissions factors from EPA, eGRID database, Economic Input-Output Life Cycle Assessment model, or Comprehensive Environmental Data Archive model	Data from EU policy analysis models (historical and projected data)	Data from meta-analysis (includes 63 studies based on authors' inclusion criteria)
Domain and behaviors measured	17 household actions in the housing and transportation domains	13 household actions in the housing, transportation and food domains	11 household actions in the housing, transportation and food domains	14 dietary change scenarios in the food domain (scenarios model different levels of meat reduction)
Model	Their behavioral approach combines data on potential emissions reduction and behavior plasticity (i.e., reasonably achievable emissions), gathered from literature.	Consumption-based accounting model.	7 policy analysis models (e.g., Assessment of transport strategies) are used to model behavioral options and their maximum realistic potential (i.e., considers constraints, indirect effects, rebound effects).	Different models used for each study. They report the number of studies and median across studies.
GHG unit	Millions of metric tons of carbon (MtC/national emissions/year)	Metric ton of carbon dioxide equivalent (Mt/household/year)	Million tonnes of carbon (MtC/European emissions/year)	Kilograms of carbon (Kg CO_2e/capita/year)
Findings	Data extracted from Table 1 in Dietz et al (2009). Realistic reductions are reported (potential reduction, not corrected for behavioral plasticity, in parentheses). Thermostat: 4.5 MtC (10.1 MtC) Fuel-efficient vehicle: 31.4 MtC (56.3 MtC) Eco-driving: 7.7 MtC (24.1 MtC) Line-drying: 2.2 MtC (6 MtC)	Data extracted from Figs. 1 and 5 (average GHG) in Jones and Kammen (2011). The relative footprint by behavior, reported in parentheses, was calculated using ($Beh_i = B_i/A$). Small change in diet: 1.7 Mt CO_2e (22.6% of food domain) Thermostat: 1 Mt CO_2e (6.9% of housing domain) Fuel-efficient vehicle: 1.6MtCO_2e (10.4% of transport domain) Eco-driving: 1.3MtCO_2e (8.4% of transport domain) Teleworking: 0.86 Mt CO_2e (6.4% of transport domain) Line-dry: 0.14MtCO_2e (1% of housing domain)	Data extracted from Table 1 (realistic potential, high and low) in Faber, Shroten et al (2012). Diet: 50 to 266 MtC Thermostats: 22 to 45 MtC Fuel-efficient vehicle: 80 to 96 MtC Eco-driving: 47 MtC Teleworking: 35 to 45 MtC Total projected at 2400 MtC for EU year 2020 (Faber et al., 2012a,b)	Data as reported in Aleksandrowicz et al (2016). Across all 14 dietary scenarios modelled: 22% median food footprint reduction Vegan scenarios: 45% median food footprint reduction (up to 72%) Vegetarian scenarios: 31% median food footprint reduction Health guideline scenarios: 12% median food footprint reduction
Formula applied	Ach_i = realistic reduction/total household footprint (potential reduction, not corrected for plasticity, in parentheses)	$Ach_i = Dom_i$ X Beh_i	Ach_i = realistic potential/total projected	$Ach_i = Dom_i$ X Beh_i (i.e, median)
Achievable GHG emissions reductions	Thermostat: 0.71% (1.62%) Fuel-efficient vehicle: 5.02% (9%) Eco-driving: 1.23% (3.86%) Line-drying: 0.35% (0.96%) _ _	Thermostat: 1.1%–2.6% Fuel-efficient vehicle: 2%–3.3% Eco-driving: 1.6%–2.7% Line-dry: 0.2%–0.4% Teleworking: 1.2%–2% Diet: 2%–7%	Thermostat: 1%–1.9% Fuel-efficient vehicle: 3.3%–4% Eco-driving: 2% – Teleworking: 1.5%–1.9% Diet: 2.1%–11% of total	– – – – – Diet: 2%–6.8% (median across all scenarios) Up to 22.3% change is reported for one vegan scenario

[a] Five reports were commissioned by the European Commission under the contract "Behavioral Climate Change Mitigation Options and Their Appropriate Inclusion in Quantitative Longer Term Policy Scenarios" (Faber et al., 2012a,b; Köhler and Köhler, 2012; Rohde et al., 2012; Schroten, 2012). All five reports are combined and listed as part of European Commission (2012) study in the table. Each specific report is cited in the text.

automatically result in a larger relative footprint for that domain, *if* the other domains' absolute footprints stay the same.

The interplay between the absolute values of each domain and the total carbon footprint of an individual is illustrated in Fig. 1 using hypothetical household examples (extracted from Jones and Kammen, 2011). In these examples, an individual in a higher-income household has the largest *absolute* food footprint compared to the average and the lower-income household (3MtC, 2.9MtC, and 2.5Mtc/year respectively), but their *relative* food footprint is the smallest (11%, 15%, and 21% respectively). As mentioned in section 2.5, income elasticity is only one of the possible factors affecting the carbon footprint "pie" (i.e., the interplay between domains).

Comparing the relative carbon footprints of each domain across multiple studies reveals the following; food represents between 9 and 31%, transportation between 19 and 32%, and housing between 17 and 37% of the average individual's total footprint. A review of the relevant literature and the formulas used to determine the relative footprints for each domain is detailed in Table 1.

3.2. Emission reduction potential for each behavior

For all behaviors, the range of achievable GHG emissions reductions (i.e., $Ach_i = Dom_i \ X \ Beh_i$) varies based on the degree or

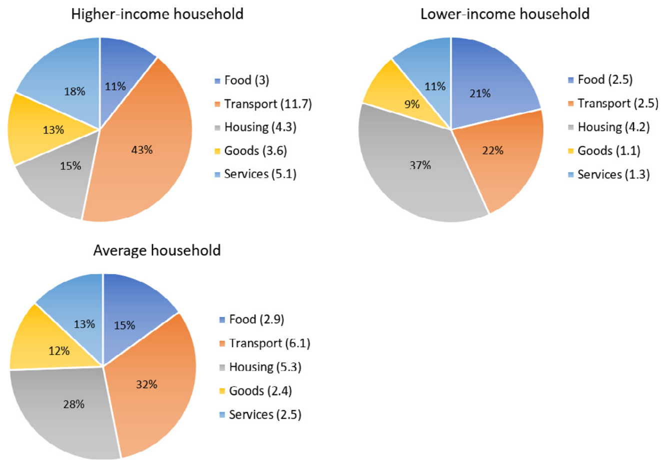

Fig. 1. Relative carbon footprints for three hypothetical American households. Note. Data extracted from Jones and Kammen (2011). Absolute carbon footprints are indicated in parentheses (MtC/year), per individual. From top to bottom a) carbon footprint of a hypothetical higher-income household (i.e., a 2-person household with a $90,000 income living in San Francisco) b) carbon footprint of a hypothetical lower-income household (i.e., a 5-person household with a $45,000 income living in St- Louis) c) carbon footprint of an average American household.

severity of behavior change modelled. The potential GHG emissions reductions associated with eating fewer animal products increases as the amount of animal products consumed decreases (e.g., vegetarian or vegan diets), and becomes considerably large if individuals are willing to completely remove animal products from their diet (Aleksandrowicz et al., 2016). In addition, the range of achievable GHG emissions reductions for each behavior, expressed as a portion of the total carbon footprint, varies based on the relative carbon footprint of each domain.

By using high and low ranges, the variability subject to the degree of behavior change and the interplay between the absolute and relative carbon footprint of each domain is embodied in our data. When looking at each behavior in isolation, clear distinctions emerge between their achievable GHG emissions reductions potential (Fig. 2). Of the behaviors studied, eating fewer animal products and switching to a more fuel-efficient vehicle have the largest potential for reducing GHG emissions. The maximum potential GHG reduction for eating fewer animal products is much larger, at over 22% of an individual's total carbon footprint (i.e., switch to a vegan diet; Bryngelsson et al., 2016), compared to 9% for switching to a more fuel-efficient car.

Maximum values for eco-driving, thermostat setbacks, and teleworking range from just under 2% to nearly 4%. Of the six behaviors included in this study, line-drying clothes instead of using a drying machine has the smallest potential to reduce GHG emissions, estimated at no more than 1% reduction of the total carbon footprint. For more details, both low- and high-points of the range of achievable GHG emissions reductions for each behavior are presented in Table 2. The range of achievable GHG emissions reductions for each behavior is presented in Fig. 2.

3.3. Air transportation

Even more so than the behaviors included up to this point in the study, the carbon footprint associated with air transportation is highly susceptible to variations in household income level and lifestyle. As mentioned earlier, a 1% increase in income leads to a 1% increase in transportation emissions (Isaksen and Narbel, 2017). However, when emissions from car use are omitted, a 1% increase in income leads to a 1.3% increase in the transportation emissions. This suggests that more luxurious modes of transportation, like flying, have higher income elasticities (Isaksen and Narbel, 2017).

Thus, unlike the other behaviors included in this study, looking

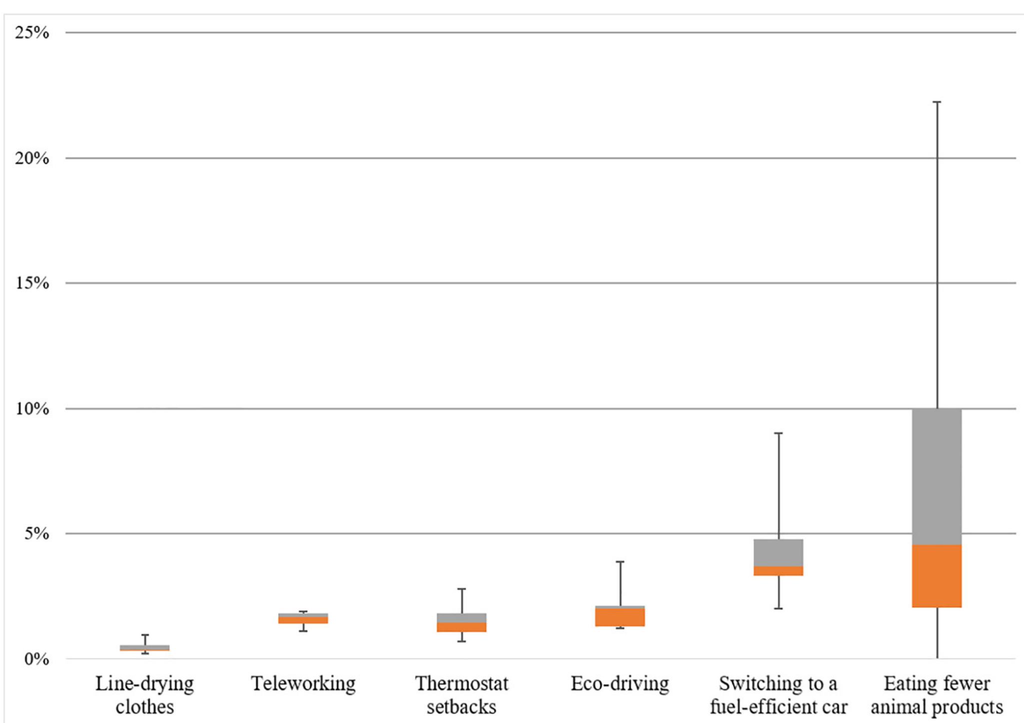

Fig. 2. Achievable greenhouse gas emissions reductions for each behavior. Note. Upper quartile, median, and lower quartile of achievable GHG emissions reductions relative to the average individual's total carbon footprint. Error bars represent minimum and maximum values.

Table 3
Carbon footprint of air transportation.

		Air transportation (baseline)	20% reduction	40% reduction	60% reduction
Average U.S. household	Flights[a]/year	2.24	0.45	0.90	1.34
	Mt CO_2e	2.15	0.43	0.86	1.29
	Air transportation footprint as % of total	4.5 %[b]	0.9 %[c]	1.8% [c]	2.7% [c]
Hypothetical higher-income household	Flights[a]/year	16.15	3.23	6.46	9.69
	Mt CO_2e	15.5	3.1	6.2	9.3
	Air transportation footprint as % of total	28.2 %[b]	5.6% [c]	11.3% [c]	16.9% [c]
Hypothetical lower-income household	Flights[a]/year	1.09	1.09	0.44	0.66
	Mt CO_2e	1.05	0.21	0.42	0.63
	Air transportation footprint as % of total	1.8 %[b]	0.4% [c]	0.7% [c]	1.1% [c]

Notes. Mt CO_2 data for each household from (Jones and Kammen, 2011). Hypothetical higher-income household is a 2-person household with an income of $90,000, Hypothetical lower-income household is a 5-person household with an income of $45,000.
[a] Based on one return flight from London to New York, which is about 0.96 Mt CO_2e (Scarborough et al., 2014).
[b] Air transportation footprint relative to the total footprint. Total household footprint estimated at 48 Mt CO_2e for average U.S. household, at 55 Mt CO_2e for the hypothetical higher-income household, and at 58 Mt CO_2e for the hypothetical lower-income household.
[c] Relative reduction in the total footprint associated with a reduction in air transportation frequency.

at household air transportation *averages* might not be very informative. Nonetheless, air transportation has a large carbon footprint, and its potential for GHG emissions reductions is worth investigating. Data from Jones and Kammen (2011) were used because they allowed to discern the variations in air transportation footprints for different household types. They modelled emissions associated with air transportation emissions (i.e., CO_2 emissions from fuel processing and combustion, and a radiative forcing multiplier of 1.9 for non-CO_2 impacts) for three household types; the average American household, a higher-income 2-person household, and a lower income 5-person household.

The average American household takes the equivalent of 2.2 round-trip transatlantic flights per year (e.g., from New York to London), whereas a hypothetical lower-income household might take only 1.1 flights per year, and a hypothetical higher-income household 16.1 flights per year (Jones and Kammen, 2011). Based on these data, a 60% reduction in air travel for a higher-income household has the potential to reduce GHG emissions by 16.9% of that household's total footprint (Table 3). In sum, although it was not deemed appropriate to use averages to compare a highly fluctuating luxurious behavior like air transportation to other less luxurious behaviors, additional analyses reveal that reducing air transportation has an undeniably large potential for reducing GHG emissions. Table 3 provides an overview of the relative footprint of air transportation for three hypothetical households.

4. Discussion

Using data available in the literature as a baseline to calculate the relative mitigation potential of individual PEBs at the household level, his study demonstrated that eating fewer animal products, driving more fuel-efficient cars, and reducing air transportation frequency are high-impact behaviors that have remarkable potential for reducing GHG emissions. For the average household in North America and Europe, eating fewer animal products had the highest achievable GHG emissions reductions potential, followed by fuel-efficient vehicles. Additional analyses demonstrated that reducing flying frequency possibly has a larger mitigation potential than fuel-efficient vehicles for the average household, depending on the degree of behavior change, and likely has the highest achievable emissions reductions potential for higher-income households taking several flights per year. For households that rarely travel by air, eating fewer animal products likely has the highest achievable emissions reductions.

This review is, to the best of my knowledge, one of the first to compare the relative impact of household behaviors. Shortly following data collection and analysis, a study comparing the potential GHG emission reductions of multiple lifestyle choices was published (Wynes and Nicholas, 2017). Wynes and Nicholas (2017) conclude that having one less child, not having a car, reducing air travel, and eating a plant-based diet have the highest impacts. Although they focus on the maximum possible GHG emission reductions for each behavior (e.g., a completely plant-based diet instead of a reduction in animal products consumed), the findings from their study are similar to the present study. Wynes and Nicholas (2017) also note that government-issued promotional material and educational systems (in Canada) overly emphasise PEBs with small-to-moderate impacts. Combined with the present findings, these two reviews provide robust support for the focus on air transportation, vehicle use/type, and reducing the consumption of animal products as PEBs with a large potential to reduce GHG emissions.

Overall, the trends in relative footprint for each domain and behavior demonstrated in this study seem to fluctuate in concordance with the characteristics modelled in previous studies. Generally, the distinctions in the range of achievable GHG emissions reductions calculated across multiple studies (Table 2 and Fig. 1) correlate with the variation in the degree of behavior change modelled in each of those studies. For example, as one might have anticipated, the study that modelled the most stringent fuel-efficiency criteria (i.e., Dietz et al., 2009) also resulted in a relatively higher estimated mitigation potential for this behavior when compared to other studies (i.e., 5% realistic reduction, see Table 2). Furthermore, the slight variations between studies in absolute and relative carbon footprints by domain are as expected. For example, countries with vast surface areas tended to have more transportation-related GHG emissions (e.g., United States at 31.8% and Germany at 23.6% of the total; Table 1).

4.1. Limitations

Some challenges are inherent to research comparing the relative mitigation potential of individual pro-environmental behaviors. The studies used to gather the baseline data vary slightly in terms of their carbon footprint models and their behavior definitions. These limitations were recognized and attempts were made to optimise the comparability of the included studies, for example, by using high and low ranges. Also, the carbon footprints vary between individuals based on several characteristics (e.g., income, country or region, household type). The values presented here are not firm, instead they offer best estimates based on a range of most likely values.

The findings are based on averages from North America and Europe (i.e., regions with a high proportion of affluent lifestyles). Results from the present study might fluctuate when applied in other regions or at smaller scales because of the regional variations in carbon footprints. For example, there are likely regional variations in terms of the quantities of animal products consumed. Also, unlike the other six behaviors reviewed in this study, only one source of data was consulted to illustrate the impact of air transportation, and it is important to reiterate that the absolute and relative carbon footprints of air travel vary significantly between households.

Because most of the data in the cited studies were gathered between 2005 and 2008, the GHG mitigation potential for some of the behaviors studied might be undervalued (e.g., more strict fuel economy standards possibly result in larger GHG reduction when switching to a fuel-efficient vehicle today compared to 10 years ago; U. S. Department of Transportation, 2014), but this is unlikely to significantly alter the relative mitigation potential of the included PEBs.

This study only included a subset of behaviors; those that were most often studied in the literature and for which data meeting the inclusion criteria were available. The list of seven (including air transportation) PEBs considered is by no means comprehensive. Other behaviors might also have a large potential for reducing household GHG emissions. For example, switching to a hybrid or electric vehicle might produce larger reductions than a conventional (or internal combustion engine) fuel efficient car, although this would strongly depend on the source of electricity. Other high impact behaviors not included here are having fewer children (Wynes and Nicholas, 2017) and reducing food waste (Hoolohan et al., 2013).

The present study did not include public-sphere PEB (e.g., voting for a candidate that favors environmental protection). These were not included because they are less amenable to quantification of GHG emissions reductions than are private-sphere behaviors. However, public-sphere behaviors indirectly can amount to sizeable GHG reductions. For example, a carbon tax priced at $25 per tonne of carbon dioxide equivalent emissions, like that of the British Columbia (Canada) carbon tax in 2011, can achieve an 8.4% reduction in per capita gasoline consumption (Rivers and Schaufele, 2015).

4.2. Implications for future research and policy

Unless otherwise indicated (e.g., Faber et al., 2012a,b), the studies consulted did not consider possible rebound effects and other behavioral limitations of PEB changes. For example, a vegetarian diet is 10% cheaper on average than a more conventional diet (Grabs, 2015). The monetary savings, if re-spent on luxury goods like air transportation, can negate part of the GHG emissions reductions (Tukker et al., 2010). However, an environmentally-motivated individual might choose to re-spend these savings on more expensive organic produce, which would limit the rebound effect (Grabs, 2015). Researchers should consider the possible interactions between PEB motivations and rebound effects during interventions.

Under ideal scenarios, households would engage in many PEBs and, combined, these would amount to significant GHG reductions (Dietz et al., 2009). However, individuals face important psychological barriers. Individuals often become numb when presented with an influx of climate change information and often feel that they have done their part after implementing only one or two PEBs (Gifford, 2011). Also, most individuals misjudge the relative importance of PEBs; individuals underestimate the climate impact of meat eating and overestimate the impact of excessive packaging, littering, and turning off lights (Attari et al., 2010; Tobler et al., 2011; Truelove and Parks, 2012).

To help individuals overcome these challenges, policymakers should focus their efforts on actions for which large GHG emissions reduction potential has already been demonstrated. Policies and programs targeting high-impact behaviors will be more cost-beneficial (i.e., more GHG emissions reductions per amount of effort). For example, the Government of Canada is currently revising its soon-to-be released Food Guide, and now recommends regular consumption of plant-based proteins (Government of Canada, 2017). Many healthy-eating guidelines coincide with climate-friendlier diets (e.g., reducing red meat consumption), and thus food policy and programs can be an effective way to help reduce GHG emissions.

Applied research targeting PEB change should consider those behaviors that have a high environmental impact, and those that have potential for change (Stern et al., 2010; Schultz and Kaiser, 2012; Capstick et al., 2014; Schultz, 2014). This study compares the direct and indirect mitigation potential of PEBs using data from several high-income countries. By quantifying the mitigative potential of different PEBs, this research provides guidance for targeting behaviors with greater GHG emission reduction. Future research should focus on finding successful interventions methods to increase the frequency for these high-impact behaviors.

4.3. Conclusion

Past research has focused on the reduction potential of direct GHG emissions in one or two household domains at a time, often overlooking indirect emissions. This study is one of the first to compare the relative impact of direct and indirect household behaviors in multiple domains. Using data from published studies to calculate behavior-specific impacts relative to the carbon footprint of the average household in North American and Europe, clear distinctions emerge between the GHG mitigation potential of seven individual pro-environmental behaviors. Building from this study's findings, more effort is needed to design successful interventions targeting sustainable food choice (i.e., reductions in meat and dairy consumption), vehicle use/purchasing decisions, and air transportation frequency.

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