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Analysis

Measurement and communication of greenhouse gas emissions from U.S. food consumption via carbon calculators

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A R T I C L E I N F O

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A B S T R A C T

Food consumption may account for upwards of 15% of U.S. per capita greenhouse gas emissions. Online carbon calculators can help consumers prioritize among dietary behaviors to minimize personal "carbon footprints," leveraging against emissions-intensive industry practices. We reviewed the fitness of selected carbon calculators for measuring and communicating indirect GHG emissions from food consumption. Calculators were evaluated based on the scope of user behaviors accounted for, data sources, transparency of methods, consistency with prior data and effectiveness of communication. We found food consumption was under-represented (25%) among general environmental impact calculators ($n=83$). We identified eight carbon calculators that accounted for food consumption and included U.S. users among the target audience. Among these, meat and dairy consumption was appropriately highlighted as the primary diet-related contributor to emissions. Opportunities exist to improve upon these tools, including: expanding the scope of behaviors included under calculations; improving communication, in part by emphasizing the ecological and public health co-benefits of less emissions-intensive diets; and adopting more robust, transparent methodologies, particularly where calculators produce questionable emissions estimates. Further, all calculators could benefit from more comprehensive data on the U.S. food system. These advancements may better equip these tools for effectively guiding audiences toward ecologically responsible dietary choices.

1. Introduction

1.1. Climate change and the role of carbon calculators

Climate change poses global threats to public health, the environment, agriculture, equity and the economy (IAASTD, 2008; IPCC, 2007; Patz et al., 2005; Patz et al., 2007; Stern 2007). In response to these threats, and to the recognition that the increase in atmospheric greenhouse gas (GHG) concentrations is largely due to human activities (IPCC, 2007) from a small number of countries — especially the U.S. (WRI, 2008) — individuals in the U.S. are increasingly seeking to reduce their personal "carbon footprints," or the amount of GHG emissions attributable to their behavior[1]. To help people understand and measure their carbon footprints — the overall magnitude of their impacts, and the relative contributions of different activities — many organizations have developed online "carbon calculators."

Despite a willingness to make personal behavior changes to reduce their climate impacts, individuals may lack the knowledge to make effective choices. Carbon calculators can address these knowledge gaps by communicating the extent to which different behaviors contribute to GHG emissions.

Among emissions-intensive behaviors, food consumption is a heavy contributor to "indirect" emissions, or "embodied" emissions in products that result from activities prior to purchase (in contrast to "direct" emissions from behaviors such as vehicle and household energy use, which may seem more obvious to the public). On the production side, these activities include agriculture, processing, transport, storage and retail.

Globally, agricultural activities and deforestation account for an estimated 31% of anthropogenic GHG emissions (IPCC, 2007); livestock production alone accounts for an estimated 18% (Steinfeld et al., 2006). Studies in the U.S. and E.U. single out consumption of meat, or specifically red meat, as the greatest contributor to indirect emissions from food consumption (Eshel and Martin, 2005; Jones et al., 2008; Nijdam et al., 2005; Tukker et al., 2006; Weber and Matthews, 2008). This is not surprising given the emissions-intensity of production (Koneswaran and Nierenberg, 2008) and the fact that the U.S. is regularly among the top meat consuming countries in the world (FAOSTAT, 2008; USDA FAS, 2008).

Although U.S. agricultural production accounts for a lower percentage of nationwide emissions than the global average (IPCC,

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[1] Use of the term "carbon footprint" varies widely across literature. Although Weidmann and Minx (2007) propose a definition that encompasses CO2 emissions only, popular literature frequently uses the term to refer to the CO_2 equivalent of multiple GHGs. We have adopted the latter use in this paper, encompassing the GHGs included under the scope of the referent study (typically CO_2, CH_4 and N_2O).

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2007), reductions in per capita diet-related emissions represent a sizeable opportunity to reduce the overall national burden on the climate. There are few U.S.-based studies that attempt to quantify these emissions; one that accounts for a relatively comprehensive breadth of the U.S. food system is the economic input–output life cycle assessment (see Section 1.3 for explanation) by Weber and Matthews (2008). Their research indicated that the average U.S. diet accounts for an estimated 3.1 metric tons (t) CO_2 equivalent (CO_2e) per capita indirect emissions annually, roughly 15% of total U.S. per-capita CO_2e emissions (U.S. Census Bureau, 2008; EPA, 2009; Weber and Matthews, 2008)[2]. Land use impacts are excluded from these estimates (Weber and Matthews, 2008).

The significance of the food system as a contributor to GHG emissions underscores the role of diet in reducing per-capita emissions Information on indirect emissions gleaned from carbon calculators can empower consumers to adopt climate-mitigating dietary behaviors, exerting pressure on industries to modify supply-side practices. Achieving these ends, however, depends on the robustness of carbon calculators.

Prior studies have identified areas where the scope, transparency and consistency of carbon and ecological footprint calculators could be improved. Lenzen and Smith decry the exclusion of product consumption in calculators, an omission of scope that perpetuates the misconception that individuals are only responsible for emissions resulting from household energy and vehicle use (Lenzen, 2001; Lenzen and Smith, 2000). A lack of transparency in calculator methods was another common finding (Kenny and Gray, 2009; Padgett et al., 2008), a potential source of frustration for anyone wishing to look "under the hood" to investigate the soundness of the calculating "engine." Finally, variations in calculator scope and methods can lead to widely varying results, or even contradictory information, across calculators (Kenny and Gray, 2009; Padgett et al., 2008; Rousse, 2008). In general, given the many variables and variations in process and practice, the findings from calculators should be presumed to represent ballpark figures rather than exact captures of individuals' GHG emissions. That said, this lack of consistency has implications for behavioral responses in users, and for the perceived credibility of calculators.

Finally, the ability to reach audiences with a palatable message about diet and climate change is a key consideration in the effectiveness of a carbon calculator. Audiences represent a broad spectrum of prior beliefs, motivations and stages along the road to adopting climate-mitigating behavior change. Put simply, even the most accurate and comprehensive calculator has little value unless it reaches a willing and able audience with a clear message.

1.2. Purpose of this review

This review builds upon prior research on carbon calculators, adopting an evaluative framework that encompasses scope, methods, transparency, consistency and effectiveness of communication to determine how, if at all, carbon calculators account for food consumption in the U.S. Dietary impacts on climate change represent a critical area for public knowledge and behavior change that has yet to be investigated, to our knowledge, with regards to carbon calculators. This research is valuable in identifying data gaps and opportunities to improve messaging through these important tools.

Given the role of carbon calculators in educating the public and suggesting priorities for behavior change, particularly with regard to food consumption, this paper addresses the following questions:

1) Scope: Among online carbon footprint calculators targeted to individuals in the U.S., which dietary behaviors, if any, are taken into account? Where a life cycle approach is used, which stages of the product life cycle are taken into account?
2) Methods: How are these emissions calculated?
3) Transparency: How transparently are methods explained?
4) Consistency: Are results for diet-related emissions consistent across calculators with prior studies?
5) Effectiveness of communication: Are diet-related emissions results conveyed to users in such a way as to promote knowledge and encourage steps toward dietary behavior changes?

1.3. Methods for calculating diet-related emissions

To help readers better understand the underlying data and assumptions that drive carbon calculators, common approaches to calculating food-related emissions are briefly introduced here.

Carbon calculators estimate climate impacts using predefined "conversion factors" that translate user behaviors ("input," e.g. buying a 4 oz. hamburger, following a vegetarian diet, etc.) to the resulting GHG emissions ("output"). Several approaches to determining conversion factors are described here in the context of diet-related GHG emissions:

Process life cycle assessment (PLCA) sums the impacts of each activity directly or indirectly involved in the production, transport, storage, retail, consumption and disposal of a particular food from "farm to fork" or "farm to waste". For example, for industrially-produced beef, these activities might include the production and application of agricultural chemicals for feed crops, transportation of feed to feedlot, ruminant emissions from cattle, energy use in feedlot and slaughter, packaging, transportation, refrigeration and retail — just to name a few.

Economic input–output life cycle assessment (EIOLCA) models the life cycle impacts of a food based on economic and environmental data on the industries involved. EIOLCA is used to estimate the emissions associated with a given amount of spending on an industry at the national level. Weber and Matthews' assessment of the U.S. food system (Weber and Matthews, 2008) is one illustrative example.

Comparing EIOLCA and PLCA, EIOLCA results are limited to broad industry-level estimates such as grain, cattle or poultry production, while PLCA results are specific to food type, geographic context and exact mode of production. Further, EIOLCA industry data is generally comprehensive and readily available, whereas PLCA models often depend on incomplete data sources, particularly for U.S. food production. Additional strengths, limitations and details of LCA methods are described in the literature (Garnett, 2008; Hendrickson et al., 1997; ISO, 2006; Kim et al., 2008; Minx et al., 2008).

Other approaches combine a variety of sources and methods. For example, Eshel and Martin's (2005) analysis — widely cited in popular literature and carbon calculators — assigned GHG emissions to dietary lifestyles (e.g. vegan, vegetarian, U.S. average) based on a combination of the estimated energy inputs required of various foods as calculated by Pimentel and Pimentel (1996), combined with the estimated methane and nitrous oxide emissions from enteric fermentation and manure resulting from meat production.

2. Methods

2.1. Calculator search

We identified an initial pool of calculators using the Google engine. It was presumed that Google searching is a common means of identifying calculators. Since Google's "PageRank" system — modeled after academic citation literature — is intended to prioritize results with the highest relevancy (i.e. most back-linked — or "cited" — by other relevant sites) and the most user visits (Brin and Page, 1988), it follows that calculators listed among initial search results were likely those most frequently used by the public.

[2] We divided Weber and Matthews' estimate of average U.S. household emissions by U.S. Census household size data, then divided the resulting value by EPA per-capita emissions estimates to achieve relative percent contributions.

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The compound Boolean search covered a selection of common keywords:

> allintitle: carbon OR CO_2 OR emissions OR "environmental impact" OR footprint OR foodprint OR "global warming" OR ghg OR "greenhouse gas" [AND] calculator OR "calculation tool" OR "footprint tool" OR "footprinting tool" OR "measurement tool"

Searches were performed in August 2008. Within the first 150 search results, we identified all individual and/or household calculators that measure direct and/or indirect environmental impacts. Calculators designed to measure impacts from activities performed by specialists and/or on an industrial level, or requiring technical expertise (e.g. LCA modeling tools) were disregarded.

Among these identified calculators, we selected those that account for dietary behaviors in calculating environmental impacts. Calculators that only account for food-related processes downstream of product purchase (e.g. home delivery, preparation, refrigeration, food waste) were excluded from this group, since these largely direct impacts are typically accounted for under transportation, household energy use and household waste.

Finally, among calculators that consider dietary behaviors, we selected those that reported GHG emissions and that include U.S. users among the target audience. These were reviewed for their accounting of diet-related emissions, through an evaluative lens that encompassed scope, methods, transparency, consistency and effectiveness of communication.

2.2. Evaluative lens

2.2.1. Scope

We defined scope as encompassing the range of user behaviors (inputs) and impacts (outputs) accounted for in calculations. With regard to dietary behaviors, scope extends to food type, mode of production, level of granularity (detail) and how consumption is quantified (e.g. frequency, quantity). Where a life cycle approach is used, scope also defines the life cycle stages accounted for (e.g. "cradle-to-gate").

2.2.2. Methods and transparency

We investigated calculator methods where transparency allowed. In cases where a lack of transparency hindered investigation of sources, calculator developers were contacted via email. If emails were not returned, we attempted to contact developers by phone.

2.2.3. Consistency

We evaluated the consistency of diet-related emissions from calculators against prior studies. Although not a measure of accuracy, cross-calculator comparisons are also provided. Calculator results for following dietary lifestyles (e.g. vegan, vegetarian, U.S. average, etc.) and for choosing organic, local or seasonal foods were evaluated independently of each other. All results were converted to metric tons (t).

Some amount of variation and uncertainty among calculator results was expected, for several reasons. First, we assumed some amount of diversity in how individuals and calculators define dietary lifestyles. The actual composition of vegan, vegetarian and high meat diets can vary widely — only the U.S. average diet has consistently defined criteria. Second, a scarcity of comprehensive, peer-reviewed data on GHG emissions from U.S. food production precludes any precise quantitative evaluation of calculator results.

Taking these limitations into account, we evaluated the plausibility of calculator results by making qualitative comparisons against prior data from established sources. These estimates include:

1) Weber and Matthews' (2008) estimate, based on EIOLCA, of 8.1 t CO_2e emissions per household, converted to per capita emissions of ~3.1 t (U.S. Census Bureau, 2008). Land use impacts are excluded from this figure.
2) Estimated U.S. emissions from agricultural activities (469.8 teragrams [Tg] CO_2e), based on 2007 EPA estimates (EPA, 2009). This figure accounts for EPA's baseline value for agricultural emissions (413.1 Tg) plus activities related to fertilizer production (30.7 Tg), agricultural equipment (48.4 Tg) and use of cropland and grassland (−22.4 Tg). This figure was divided over the 2007 population (U.S. Census Bureau, 2008) to obtain a per capita estimate of 1.56 t. This figure represents an underestimate of diet-related emissions, given the exclusion of non-agricultural emissions sources and certain embodied emissions in imported products.

2.2.4. Dietary lifestyle emissions estimates for the CoolClimate Carbon Calculator and Low Carbon Diet Calculator

Two of the calculators selected for review, developed by the Berkeley Institute for the Environment (BIE) and the Bon Appétit Management Company Foundation (Bon Appétit), based emissions on the quantities of foods consumed by the user. Other calculators reviewed, in contrast, based emissions on users' dietary lifestyles. For comparative purposes, we extrapolated the results from BIE and Bon Appétit to estimate the annual per-capita emissions from dietary lifestyles.

To determine annual emissions, we developed four representative diets. 1) The *U.S. average* diet was based on USDA food availability data (USDA ERS, 2009a). These data represent annual food supply, excluding exports, farm inputs and industrial uses. Food availability data overestimate actual consumption since spoilage and food waste are not accounted for; however, they provide a more holistic picture of the indirect impacts associated with consumption. These data were supplemented with supporting sources (Davis and Lin, 2005; MyPyramid.gov, 2009) to estimate consumption of specific food items.

Data for the U.S. average diet were entered into Bon Appétit's calculator. Where food items from the USDA data did not have similar equivalents in the calculator, we identified proxy foods (e.g. soda was used as a proxy for fruit drinks and cocktails); in a few cases where no suitable proxy was available, those foods were excluded from calculations, resulting in a slight underestimate.

Representative 2) vegetarian, 3) vegan and 4) high red meat diets were designed to meet the same total caloric requirements of the U.S. average diet (USDA ERS, 2009b) while adjusting the relative consumption of food types — acknowledging that typical vegans and vegetarians probably do not eat the same number of calories as the average American (Haddad and Tanzman, 2003, also see Section 4.2), but using this assumption makes our analysis parallel to those used in other reviewed carbon calculators. Using the U.S. average diet as a baseline, relative changes in consumption for the vegetarian and vegan diets were based on analysis of the Continuing Survey of Food Intake by Individuals (Haddad and Tanzman, 2003). The high red meat diet assumes calories from poultry and fish are replaced entirely by red meat sources, consistent with the definition used by other calculators and Eshel and Martin (2005).

Using calculator results for the U.S. average diet as a baseline, we calculated percent changes in GHG emissions for the vegan, vegetarian and high red meat diets based on relative changes in consumption of each food type. The resulting estimates reflect how the two calculators would evaluate each diet when followed by an individual for one year (see Table 3).

2.2.5. Effectiveness of communication

We reviewed calculators for whether and how they utilize the following mechanisms that may promote knowledge and/or more effective communication for behavior change:

1) Reporting emissions from food consumption separately from other behaviors, and/or parsing emissions by food type.

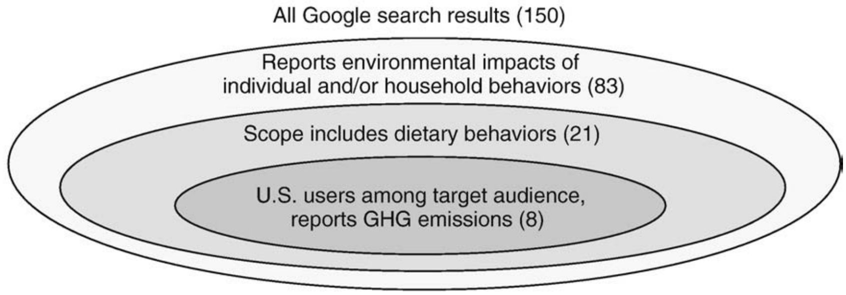

Fig. 1. Sets of identified calculators.

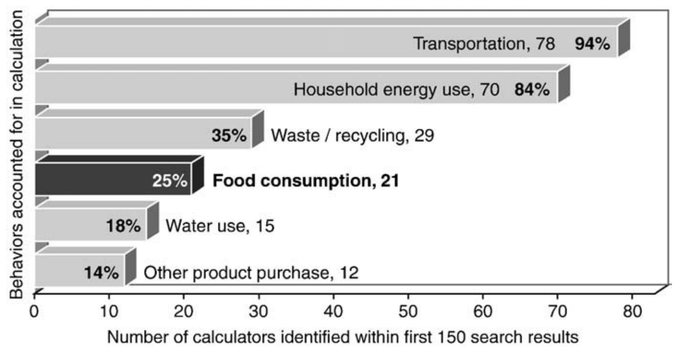

Fig. 2. Distribution of behaviors included under scope of all identified calculators.

2) Providing information regarding sources and causes of GHG emissions from food systems.
3) Reporting co-benefits of climate-mitigating dietary behavior changes, either to appeal to a broader set of beliefs/motivations or to target a specific audience with particular beliefs/motivations.
4) Accounting for audiences at various stages of behavior change.
5) Providing recommendations on how to reduce emissions from food consumption, and/or other guiding/efficacy enhancing features.

2.3. Follow up

Following review, we attempted to contact calculator developers where our findings suggested unclear or questionable methods. Where developers have modified their calculators since the initial search, either independently or in response to this review, for the sake of consistency we report all findings as they were originally recorded, while also making note of significant known updates.

3. Results

3.1. Summary of findings

Fig. 1 depicts the findings, grouped by general calculator criteria, among the first 150 relevant search results. Fig. 2 shows the distribution of behaviors included among these calculators. Of the first 150 search results, 83 calculators measured the impact of individual or household behaviors. While the majority considered transportation (94%) and/or household energy use (84%), only 21 (25%) accounted for food consumption in calculating environmental (GHG emissions, ecological footprint) or economic (money saved, cost of environmental damages) impacts. Of these, most considered only one or two dietary behaviors. Information regarding meat consumption was the most common user input requested. Of the 21 calculators that considered food consumption, we identified 10 that included U.S. users among the target audience, of which eight reported GHG emissions. This subset, depicted in Table 1, was selected for detailed review.

3.2. Scope

Fig. 3 shows the distribution of dietary behaviors among reviewed calculators. Table 2 summarizes the scope of user behaviors among these calculators. This table shows the variation in how calculators accounted for user food consumption — for example, whether or not the scope encompassed the type of food(s) consumed and/or how that food was produced; in addition to how consumption was measured, e.g. by spending, quantity, frequency or general dietary lifestyle.

Table 1
Carbon calculators selected for review[a].

Developer, (most recent date of update), *title*	URL
The Berkeley Institute of the Environment (BIE) (2008) *CoolClimate Carbon Footprint Calculator*	http://coolclimate.berkeley.edu/
Bon Appétit Management Company Foundation (Bon Appétit) (2008) *Low Carbon Diet Calculator*	http://www.eatlowcarbon.org/
Carbon Footprint (2008) *Carbon Footprint Calculator*	http://www.carbonfootprint.com/calculator.aspx
Carbonify.com (n.d.) *Carbon Dioxide Emissions Calculator*	http://www.carbonify.com/carbon-calculator.htm
Clearwater (2005) *Clearwater Carbon Calculator*	http://www.clearwater.org/carbon.html
Conservation International (2008) *Carbon Calculator*	http://www.conservation.org/act/live_green/carboncalc/Pages/default.aspx
The Nature Conservancy (2008) *Carbon Footprint Calculator*	http://www.nature.org/initiatives/climatechange/calculator/
Stop Global Warming (2008) *Carbon Calculator*	http://www.stopglobalwarming.org/carboncalculator.asp

[a] All calculators cited August 2008.

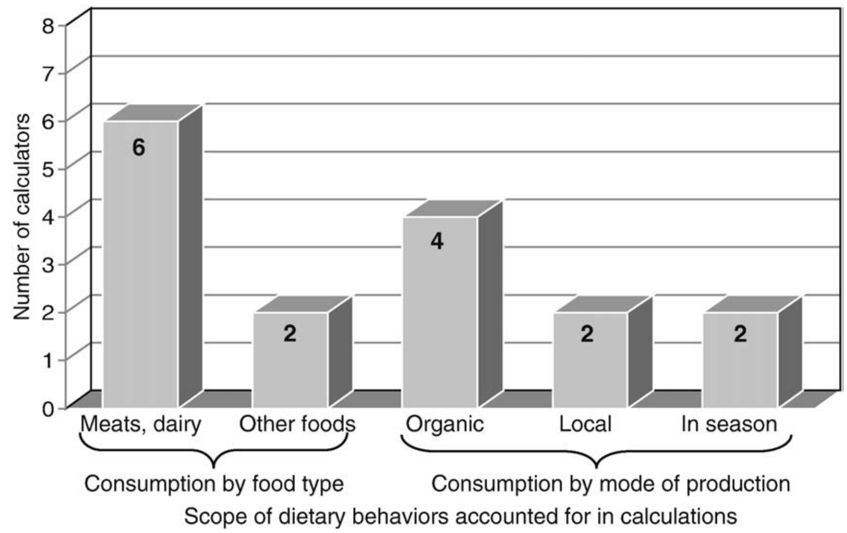

Fig. 3. Distribution of dietary behaviors included under scope of reviewed carbon calculators.

3.2.1. User behaviors

Meat consumption was the most common (six of eight) user behavior under food type, appropriately reflecting the substantial role of meat production in contributing to GHG emissions.

Granularity of food type ranged from broad food categories to specific meal items. Clearwater aggregated all foods into a single category. Carbonify.com aggregated meat consumption as a single category. Conservation International and The Nature Conservancy considered degrees of meat consumption by dietary lifestyle (e.g. omnivore, vegetarian). Carbon Footprint made additional distinctions between meat type (fish, white meat, red meat). BIE parsed food consumption into categories such as dairy, fruits & vegetables and cereals & bakery products. Although BIE offered more granularity in food inputs than most calculators, the grouping of meat, fish & eggs made it difficult to estimate the emissions of lacto-ovo-vegetarian and high red meat diets[3]. Similarly, the absence of a distinct category for high-protein plant-based foods such as nuts and legumes limits the calculator's use among vegan audiences, since these common meat-substitutes may have lower embodied emissions than other fruits & vegetables. Bon Appétit's was the only calculator to consider highly specific meal items, such as roasted turkey, farmed salmon and seasonal grilled vegetables.

Among the two calculators that used a life cycle approach to measure emissions, BIE covered "farm-to-consumer" emissions, including those from transport to market and retail/wholesale trade (communication with Christopher M. Jones, April 2009). Bon Appétit covered "farm-to-fork" emissions, including those from food preparation.

Five calculators considered user preference for foods that are organically produced, grown in-season and/or locally distributed. Among these preferences for modes of production, organic was the most frequently represented, included in four calculators.

3.2.2. Impacts

Ambiguous and inaccurate use of terminology made it difficult to determine which emissions were reported by calculators (this was also an issue of transparency). With one exception, we assumed all calculators reported annual GHG emissions as mass of CO_2e, accounting for CO_2, methane and N_2O emissions. Three of these calculators incorrectly reported CO_2 rather than CO_2e, while methane and N_2O were only clearly mentioned in one calculator. By examining the sources used in estimating conversion factors, we confirmed the inclusion of methane and N_2O in these calculators — with the exception of Clearwater, which explicitly stated that it accounted for carbon emissions only.

3.3. Calculation methods

The carbon calculators we reviewed drew from a variety of methods and sources, including PLCA, EIOLCA, and Eshel and Martin's work (2005). Some calculators brought together multiple sources to determine conversion factors, and at times relied on proprietary in-house calculations.

BIE sourced the U.S. economic input–output life cycle assessment (EIOLCA, see section 1.3) database (CMU, 2008) to calculate emissions associated with user spending on various food categories. Each category was an aggregation of multiple food industries, e.g. meat, fish & eggs.

Bon Appétit drew from process life cycle assessments (PLCAs, see section 1.3) to determine "farm-to-fork" conversion factors for

Table 2
Scope of dietary behaviors among reviewed carbon calculators[a].

	Food type		Mode of production		
	Meats, dairy	Other foods	Organic	Local	In season
BIE	Spending	Spending			
Bon Appétit	Quantity	Quantity		Quantity (fish only)	Quantity
Carbon Footprint	Dietary lifestyle		Frequency	Frequency	Frequency
Carbonify.com	Dietary lifestyle				
Clearwater[b]			Spending		
Conservation International	Dietary lifestyle				
The Nature Conservancy	Dietary lifestyle[c]		Frequency		
Stop Global Warming			Frequency	Frequency	

[a] Spending, quantity, frequency, and dietary lifestyle denote user input entered as spending in USD on foods, quantity of food consumed, frequency of food consumption, or dietary lifestyle (e.g. vegetarian, omnivore), respectively.
[b] Clearwater aggregates all food into a single general category.
[c] Although The Nature Conservancy prompts users for frequency of meat consumption, each frequency (e.g. at most meals, rarely, never) translates to a dietary lifestyle (e.g. high meat, lacto-ovo-vegetarian, vegetarian/vegan).

[3] BIE's second generation calculator, soon to be available through www.coolcalifornia.org, is slated to offer a more granular scope of inputs.

hundreds of specific foods, including seasonal produce. A shortage of data regarding U.S. food production necessitated use of some European PLCA data as proxies, with modifications wherever possible to better adapt data to a U.S. setting (Scholz et al., 2008). Unlike other calculators designed to report annual emissions, Bon Appétit reported emissions for individual meals.

Carbon Footprint based diet-related emissions calculations on data from the UK Department of Energy, Food and Rural Affairs (DEFRA), with no known modifications for U.S. food production. Further details on methodology were not made available.

Carbonify.com used Eshel and Martin's (2005) estimation that the average U.S. diet is responsible for ~1.5 t more per-capita emissions than an entirely plant-based diet. Based on our initial findings, this calculator ostensibly attributed 1.5 t CO_2e to diets with meat and 0 t to non-meat diets. The developer has since responded to our review by attributing 3.3 t CO_2e to the average U.S. diet pooled with household waste and 1.8 t to a vegan diet pooled with household waste.

Clearwater translated expenditures on food to equivalent gallons of gasoline, and subsequently to the carbon emissions (not CO_2) resulting from combustion. Our analysis revealed Clearwater's formula was based on a faulty assumption that organic food production produces zero carbon emissions. Clearwater did not state this assumption in their methods description.

Conservation International drew from multiple sources to estimate emissions associated with vegan, vegetarian, “mostly vegetarian” and omnivorous diets. Sources encompassed studies on energy use in the food system, including those by Eshel and Martin (2005), Pimentel and Pimentel (1996) and Annika Carlsson-Kanyama (2000); FAO's report on livestock production (2006); Weber and Matthews's EIOLCA research on “food-miles” (2008) and others. Exact methods on how these sources were utilized were not made available.

The Nature Conservancy cited EPA agricultural emissions estimates (2008) in calculating average U.S. diet-related per-capita emissions. EPA emissions that were not directly attributable to individual behavior (e.g. certain industrial activities) were distributed across behavior categories (diet, transportation, household energy, etc.); as a result, The Nature Conservancy's estimate for diet-related emissions was higher than the per capita EPA estimates for agricultural activities alone (appropriately so). Where the composition of user diets deviated from the U.S. average, relative percent changes in emissions resulting from vegan, vegetarian or high red-meat diets were applied based on average caloric consumption of food types (from U.N. FAO data, summarized in Eshel and Martin [2005]) and their associated contributions to GHG emissions (based on EPA emissions data, parsed by food type). Finally, a percent reduction in emissions was awarded for organic consumption, based on Pimentel's analysis of the Rodale trial (Pimentel et al., 2005) — a long-running comparison between organic and conventional cropping systems.

Although specific studies are not provided, Stop Global Warming presumably based avoided emissions estimates from “always” buying organic foods on the Rodale trial (Pimentel et al., 2005). Emissions savings from eating “local food once a week” were attributed to avoiding the “typical 1500 miles” for delivery, erroneously suggesting emissions from transporting food within localities are nonexistent.

3.4. Transparency

Our review of methods was constrained by limitations on transparency. Five calculators provided conversion factors used to calculate emissions; though some other conversion factors could be imputed based on how user response affects emissions results. Only three calculators noted specific studies on which conversion factors are based. Regarding Bon Appétit, providing full transparency for LCA sources would have been overwhelmingly cumbersome and limited by constraints on proprietary data sets. Three calculators provided the scope of GHG emissions reported; the other five did not explicitly state whether they report CO_2 emissions only, or additionally methane, N_2O and other GHG emissions.

Via email and phone communication with developers and investigation of sources, we gleaned some additional information regarding methods and scope of impacts. Even with this additional information, only BIE, Carbonify.com and Clearwater and The Nature Conservancy provided complete transparency of scope and methodology, including sources.

3.5. Consistency

3.5.1. Dietary lifestyle

Table 3 shows the annual per-capita GHG emissions from food consumption, converted to metric tons (t) CO_2e, reported by five calculators for select diets: vegan, vegetarian, U.S. average/omnivorous and high red meat diets. As expected, there is an overall consensus that higher meat consumption increases GHG emissions, despite considerable variation across calculators. Not all diets were possible to evaluate with all calculators due to limitations in scope. Due to the qualitative nature of some dietary categories (e.g. “omnivore,” red meat “at most meals”) and variations in assumptions (e.g. total calories consumed, percent caloric consumption from animal products) and scope, some direct comparisons are not valid. Included, for comparative purposes, are data from Weber and Matthew's EIOLCA study (Weber and Matthews, 2008) and the EPA (for agricultural activities only, as defined in Section 2.2.3).

BIE reported U.S. average annual household diet-related emissions at 6.7 t, or 2.6 t per capita, assuming a household size of 2.59 persons (U.S. Census Bureau, 2008). Estimates for vegan and vegetarian diets (see Section 2.2.4 for our definitions of these diets) were unusually high due to an inability to parse out certain food types (see Section 3.2.1).

Although not intended for this purpose, Bon Appétit's results were extrapolated to estimate annual per-capita emissions for U.S. average, vegan, vegetarian, and high red meat diets (see Section 2.2.4).

Carbonify.com's misapplication of Eshel and Martin's results to a baseline zero emissions for a vegan diet resulted in underestimates by any standard, though this has since been addressed by the developer. Similarly, Carbon Footprint's estimated emissions were consistently low across dietary categories. For example, reported total emissions for “eating red meat every day” (1.59 t) were barely over EPA estimations for the agricultural component only of the average U.S. diet (1.56 t).

Conservation International's results were generally higher than other calculators, particularly for a vegan diet.

Table 3
Reported annual per-capita GHG emissions (metric tons CO_2e) for select diets.

	High red meat	U.S. Average or omnivorous	Vegetarian	Vegan
Calculators reviewed				
BIE	N/A[a]	2.59	2.41[b]	2.33[b]
Bon Appétit	3.24[b]	2.78[b]	1.85[b]	1.53[b]
Carbon Footprint	1.59	1.31[c]	0.47	0.19
Carbonify.com	N/A[a]	1.5[d]	N/A[a]	0[d]
Conservation International	N/A[a]	3.8[c]	2.7	2.0
The Nature Conservancy	5.26	3.72	1.36	0.82
Comparative figures				
EPA, agriculture only[e]		1.56		
Weber and Matthews		3.1		

[a] Calculator does not provide sufficient information to calculate emissions for this diet.
[b] Based on manual calculations. See Section 2.2.4 for assumptions.
[c] Defined as “omnivorous” or “a mix of red and white meat."
[d] The developer has since updated these estimations to 3.3 and 1.8 for U.S. average and vegan diets, respectively. These diet-related emissions estimates are bundled with household waste.
[e] As defined in Section 2.2.3.

Among calculators that used discrete dietary categories, The Nature Conservancy reported the broadest range of values, as well as the highest estimate for a high red meat diet category.

3.5.2. Mode of production

Among calculators reviewed, emissions benefits of organic and local foods were generally overstated compared to prior studies.

The Nature Conservancy applied a reduction in baseline diet-related emissions of up to 29% for users who consume organic foods "most of the time." This amounted to 1.08 t of avoided emissions based on their estimate for the U.S. average diet.

Stop Global Warming attributed a reduction of 1.81 t "CO_2" (presumably CO_2e) for "always" buying organic foods. This overestimated value is a larger savings than would be achieved by eliminating all animal products from the average U.S. diet, based on most estimates.

At the lowest extreme, Clearwater assumed organic food consumption results in zero emissions.

Regarding local foods, Stop Global Warming attributed a reduction of 2.27 t CO_2 to eating local "once a week." These savings were heavily overestimated compared to existing data. 2.27 t CO_2 represents 73% of the total average U.S. diet-related emissions of 3.1 t CO_2, by Weber and Matthews' estimate (2008). In contrast, Weber and Matthews (Weber and Matthews, 2008) estimate only 4–5% of total U.S. food life cycle GHG emissions are attributable to "food miles."

3.6. Effectiveness of communication

3.6.1. Parsing impacts by behavior category

Five calculators reported diet-related emissions independently of emissions from other activities. BIE was the only calculator to parse total emissions by food categories, while Bon Appétit reported diet-related emissions only and then parsed results by specific food type.

Carbon Footprint grouped diet-related emissions with other indirect emissions. Conservation International grouped diet-related emissions in with total emissions, but it was easy enough to observe how dietary behaviors affect the total. Carbonify.com pooled diet-related emissions with household waste.

3.6.2. Explanation of GHG emissions sources within the food system

Only four calculators (Bon Appétit, Conservation International, The Nature Conservancy, Stop Global Warming) provided explanation of how the food system contributes to GHG emissions. Among these, only two gave information on emissions from livestock production, albeit on separate pages from the calculators — requiring users to navigate the site before accessing this information.

3.6.3. Appeal to varying beliefs and motivations

Most calculators reviewed made limited or no appeals to varying beliefs and motivations. Stop Global Warming reported financial savings associated with certain behavior changes. Although this may be a powerful incentive for many users, no savings were reported from choosing local or organic foods, as expected. BIE and Clearwater reported oil-use equivalents of emissions, potentially appealing to concerns about energy independence or Peak Oil. BIE, Carbonify.com and Conservation International incorporated themes of forest growth and conservation, appealing to belief in the value of nature. Bon Appétit's documentation referenced the flavor and freshness of local, seasonal foods, appealing to sensory and health motivations.

Surprisingly, no calculators reviewed emphasized co-benefits to public health, nutrition, animal welfare, local economies, community or other incentives that may be associated with less emissions-intensive diets.

3.6.4. Accounting for audience stage of behavior change

Most calculators offered a simple enough user experience to appeal to audiences in early stages of behavior change. The general guidance offered by these calculators may help direct individuals who intend to reduce their climate impact through diet. Conservation International was unique in providing the option to measure basic inputs (excluding dietary behaviors) or more detailed inputs, appealing to a broader range of audiences. The granular detail offered by Bon Appétit may appeal more to individuals who already have foundational knowledge of behavior–climate relationships, and who are seeking out more refined information. No calculators reviewed offered specific techniques to maintain long-term behavior, such as options to create an account and/or track emissions over time.

3.6.5. Provision of recommendations

Four calculators provided recommendations on how to lower diet-related emissions. Among these, three calculators suggested reducing meat consumption. For two of these calculators, recommendations were provided on a separate URL. Bon Appétit provided recommendations catered specifically to user input, in the form of alternative meal suggestions. Stop Global Warming's calculator was modeled around recommended behavior changes, and was unique in its use of positive feedback: While other reviewed calculators penalized users for emissions-intensive behaviors, Stop Global Warming rewarded users by reporting the *avoided* emissions achieved by adopting recommended behavior changes.

4. Discussion

4.1. Limitations of scope

The findings of this study suggest a general lack of consideration of diet-related emissions among carbon calculators and similar tools, under-representing the significance of diet in contributing to indirect GHG emissions. This is consistent with the relatively low coverage of food and agriculture in U.S. newspaper articles on climate change (Neff et al., 2009). Echoing Lenzen and Smith (2000), these omissions perpetuate the misconception that the primary GHG emissions of concern for individual behavior change are those resulting from household energy and vehicle use.

Within the minority of carbon calculators identified that appealed to a U.S. audience and accounted for dietary behaviors, most aggregated food consumption into broad dietary lifestyle categories. Although (arguably) creating a simpler user experience, this lack of granularity may fail to capture key distinctions such as the substantial differences in life cycle emissions between poultry and beef.

Reasons for these communication gaps include the lack of comprehensive data on GHG emissions from the U.S. food system. Further, indirect emissions from diets are particularly difficult to quantify because of the complexity in modeling food systems, variation in modes of production, regional environmental conditions for the same food that result in widely varying emissions, and at times, a lack of a 1:1 relationship between quantity consumed and emissions generated. These challenges are reflected in the repeated use of the same few available sources (e.g. Eshel and Martin, (2005)) and the use of European data as proxies in life cycle assessments, underscoring the need for additional U.S.-based research and LCA work, critical verification of existing studies and greater transparency into the food industry.

4.2. Methods and consistency

Results from different calculators are not expected to be entirely consistent, given they often reflect qualitative definitions of dietary behaviors, and express a variety of assumptions made in calculation methodologies. Further, the aforementioned lack of comprehensive data on U.S. diet-related GHG emissions makes it difficult to judge the exact accuracy of calculator estimates.

Taking these caveats into account, some calculators reported estimates that were incongruous with the available data, at times a result of drawing from inappropriate data sources or misapplying source studies. For example, Carbon Footprint reported unexpectedly low diet-related emissions estimates. This may be attributable to the use of U.K. data to represent U.S. food systems, without accounting for differences in the emissions-intensity of production. Carbonify.com also reported underestimated values by way of an assumption that vegan diets contribute zero emissions (this has since been remedied by the developer).

Among calculators that base emissions on dietary lifestyles, several are based on an assumption that average Americans, vegetarians and/or vegans consume the same amount of total calories (in our representative diets for BIE and Bon Appétit we make the same assumption, though only for consistency - see section 2.2.4.). However, data suggest vegetarians actually consume less (Haddad and Tanzman, 2003), suggesting the emissions results for these meat-free diets may be overestimates.

Calculator estimates of avoided emissions from choosing organic and/or locally-produced foods illustrate an additional challenge in accurately quantifying diet-related emissions. Both Stop Global Warming and Clearwater reported avoided emissions from choosing organic and/or local foods that far exceeded estimates that could be drawn from the literature. Even The Nature Conservancy and Carbon Footprints' more conservative estimates of the benefits of choosing organic were questionable, since the actual climate benefits of eating such foods in place of conventional alternatives are difficult to quantify. Despite evidence of reduced energy inputs, soil carbon sequestration and other environmental benefits of organic production, the overall body of research comparing relative climate impacts of organic versus conventional production is mixed and varies by food type (Casey and Holden, 2006; Cederberg and Mattsson, 2000; Garnett, 2008; Meisterling et al., 2009; Pelletier and Tyedmers, 2007; Pimentel et al., 2005; Thomassen et al., 2008). Often the differences arise because 1) the studies do not take account of the full scope of benefits of organic production, 2) the studies indicate lower yields in organic production — requiring more agricultural activities to obtain the same quantity of food and/or 3) there is tremendous variation in practice within what is considered “organic” agriculture. The variation is equally broad in definitions of “local” food. For example, while Weber and Matthews estimate U.S. “food miles” account for an average of only 4–5% of life cycle emissions, this study looks at emissions from delivery in isolation; in contrast, consumers may perceive “local food” to have been produced under certain conditions. These loose criteria make it challenging to arrive at clear, generalizable comparisons between conventional and organic/local alternatives.

Although these uncertainties make it difficult to justify avoided emissions from organic production in carbon calculators, organic/sustainable production may alleviate some of the public health, ecological and animal welfare impacts associated with conventional crop and animal production (Horrigan et al., 2002; Pew Commission on Industrial Farm Animal Production, 2008; Steinfeld et al., 2006; Walker et al., 2005). Accounting for these other impact categories could validate the inclusion of organic foods in calculators, provided the scope of the calculator extended beyond GHG emissions alone.

Overall, despite some concerns of accuracy and soundness of methods, these calculators send a clear message that the consumption of animal products — particularly red meat and dairy — is by and large the greatest contributor to diet-related GHG emissions, consistent with existing U.S. and international literature (Eshel and Martin, 2005; Jones et al., 2008; Nijdam et al., 2005; Tukker et al., 2006; Weber and Matthews, 2008).

4.3. Effectiveness of communication

A comprehensive, granular scope paired with robust methodology are two legs of a wobbly stool without effectively communicating to an audience. This is illustrated by the results of a recent U.S. survey: Among respondents who were aware of carbon calculators, less than half understood how they work (Sacred Heart University, 2009).

At the most basic level, effective communication requires reporting diet-related GHG emissions separately from the overall carbon footprint, so users can identify the relative contributions of their diets. Most calculators reviewed met this criteria; however, few offered in-depth information on the sources of these emissions within the food system. Including some explanation of how diet and climate change are linked may help users place emissions results in context and add credibility.

In addition to fostering knowledge, calculators must “win over” audiences with a convincing message. The importance of appealing to audience beliefs and motivations in fostering climate-mitigating behavior change is well documented (de Boer et al., 2009; Maibach et al., 2008; Parker and Shapiro, 2008). Among users of carbon calculators and similar tools, social norms, habitual behavior, perceptions of convenience, personal benefit (Chatterton et al., 2009) and self-identification with environmentalism (Brook and Graham, submitted for publication) were identified as major factors in adopting climate-mitigating behaviors. Calculators may appeal to these and other beliefs/motivations by communicating social, public health, nutritional, animal welfare, sensory (e.g. taste, freshness) ecological and/or economic co-benefits of adopting climate-mitigating dietary behaviors (Chatterton et al., 2009; Maibach et al., 2008), just to name a few. The prioritization of these appeals should be based on the target audience (Maibach et al., 2008).

Among calculators reviewed, surprisingly few addressed any of these co-benefits of less emissions-intensive diets. Personal co-benefits were notably absent, with the exception of Stop Global Warming's innovative appeal to cost savings. Communicating co-benefits of less emissions-intensive dietary behaviors may increase audience buy-in by appealing to a broader set of beliefs and motivations, particularly self-interest.

A fourth component of effective communication is recognizing that behavior change is a gradual process involving sequential steps (Piotrow et al., 1997; Prochaska and Velicer, 1997) and audiences represent a range of stages along this progression. For example, audiences with less diet-climate knowledge may be more receptive to a simple message that creates a basic awareness of the issue, while die-hard ecological-eaters may wish to refine their practice with more sophisticated information. Requesting some information on users' preparedness to change, and customizing the calculator experience accordingly (e.g. simplifying the experience for audiences with little or no exposure to behavior–climate issues), may broaden the reach of the calculator. Conservation International loosely met this criteria; most other calculators reviewed generally offered a balance of simplicity and content that would likely benefit users along all stages of change (where the information is *accurate*, which is a separate issue), though more research is needed in this area.

Finally, to better guide behavior changes and to alleviate potential feelings of despair upon receiving negative feedback (e.g. “your dietary carbon footprint is equivalent to driving a Hummer”), Brook and Graham (submitted for publication) recommend calculators provide specific, achievable recommendations to encourage self-efficacy and guide users in reducing their emissions. Only half of the calculators reviewed met this criteria.

This is by no means an exhaustive list of considerations — other approaches to encourage behavior change, although beyond the scope of this review, include conveying the sense that adopting ecological behaviors would be acting in concordance with the majority — the concept of “social proof.” (Cialdini, 2001).

It is worth highlighting Stop Global Warming's unique approach of reporting *avoided* emissions, alongside financial savings, resulting from adopting recommended behavior changes. This use of positive feedback (emissions avoided, rather than caused) could

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appeal to users susceptible to anxiety or defensiveness from negative feedback. Further, saving money is a powerful incentive, and could be applied to behaviors such as switching to a cheaper, lower-emissions vegan diet. Although Stop Global Warming's calculator lacked in scope and provided some unlikely results, the effectiveness of its underlying concept and method of communication merits further investigation.

While our recommendations are based on a combination of prior studies and common sense, additional research is needed to evaluate how effectively calculators elicit behavior changes, for a variety of audiences and behaviors. This raises the question of who uses carbon calculators, what their beliefs and motivations are, how well calculators are reaching these target audiences, and how the appeal of carbon calculators might be broadened to encompass broader audiences.

4.4. Recommended calculators

Among calculators reviewed, there were several based on sound methodologies, with adequate scope, that reported plausible emissions estimates. Even among these, however, none were without limitations, and selecting the “best” calculator is largely dependent on the desired intent and personal preferences of the user.

Bon Appétit's calculator was unique in its provision of a breadth of highly-specific food items, accounting (to the degree possible) for “cradle-to-plate” emissions with finely granular details. There was no option to extrapolate emissions over the course of any time span (nor would such a feature necessarily be desirable, given the inaccuracy of dietary recall), limiting this calculator's application to single meals. Although methods were based on widely accepted LCA standards for calculating life cycle emissions of products, the use of European data presents some concern; however, until a greater pool of U.S. LCA data is available, proxies are a necessity. Given what data are available, Bon Appétit provided what was arguably the best and only tool available to the public for measuring and comparing emissions from a wide variety of individual meals.

Among tools that calculate annual emissions, both Conservation International and The Nature Conservancy offered plausible emissions estimates for dietary lifestyles. With what little data is available on U.S. food system emissions, it was difficult to evaluate the accuracy of either tool, though Conservation International had the advantage of pulling from a more robust pool of sources. The Nature Conservancy offered a slightly broader scope, accounting for organic consumption and a greater variety of diets. Neither calculator offered rigorous means to incite knowledge and behavior change.

4.5. Transparency

Peer-reviews are difficult, if not impossible, for calculators that do not provide clear, accurate, specific and transparent methods and scope. Many of the calculators reviewed in this study, with their ambiguity and non-transparency around methodologies, were no exception. Without scrutiny from the scientific community, results cannot be held to a standard of accuracy and credibility. Further, a more open exchange of information between developers, researchers and the public can ensure the most up-to-date and defensible designs while increasing user confidence in the accuracy of results.

4.6. Strengths and limitations of this review

This study is limited to consideration of GHG emissions; however, certain aspects of large-scale food production contribute to a number of other impacts, many of which result in more direct and immediate consequences to human and ecosystem health than those of climate change. These include eutrophication, the release of toxins to air, water and soil; antibiotic-resistant bacteria, land and water use, biodiversity loss, topsoil erosion, animal welfare, foodborne illness, impacts to communities living in proximity to industrial farm animal production facilities and other social and economic outcomes (Horrigan et al., 2002; Pew Commission on Industrial Farm Animal Production, 2008; Walker et al., 2005). Many of these impacts are disproportionately shouldered by low-income and minority populations. On the consumer-side, many highly-processed snack foods require GHG-intensive production with few beneficial returns on nutritional value (Carlsson-Kanyama et al., 2003); reducing consumption of these foods represents one of many health co-benefits of an ecologically sound diet. Incorporating these issues into calculators, even qualitatively, can better inform diet-related behavior changes — particularly regarding foods for which climate impacts are counterbalanced by benefits (or harms) in other areas — while appealing to a broader range of concerns.

Another limitation of this study is the difficulty in capturing a meaningful static snapshot of an ever-changing selection of carbon calculators. Illustrating the evolving nature of calculators, BIE's second generation calculator — to be available through coolcalifornia.org — is slated to offer a wealth of improvements over its predecessor.

Finally, data gaps in U.S. food production preclude concrete recommendations on exact estimates for diet-related GHG emissions. We were limited to comparing calculator results against a small pool of prior research, some of which has not been adequately verified with supporting data.

Despite these limitations, the importance of communicating diet-related GHG emissions is rarely discussed in academic literature, particularly with regard to carbon calculators. Given this lack of attention, this study serves as a clarion call to environmental organizations, public health professionals and the greater academic community, highlighting needs for improved scope, methodology, transparency and effectiveness of communication in this area, as well as the need for more comprehensive research on GHG emissions from the U.S. food system and the effectiveness of carbon calculators in changing dietary behaviors.

5. Conclusions

The urgency of climate change demands informed behavior changes to reduce GHG emissions, including steps to reduce those arising indirectly from food consumption. On the principle that “what is not measured is not managed,” online carbon calculators should play a key role in quantifying and effectively communicating these emissions.

There are substantial opportunities for improving the fitness of existing carbon calculators for this purpose. Many could better educate users by adopting a broader scope that encompasses dietary behaviors. Those that already account for diet-related emissions highlight the need for more rigorous methodologies and more effective means of communication, including measures to communicate the ecological and public health co-benefits of less emissions-intensive dietary behaviors. Finally, transparency is paramount in facilitating critical reviews that ensure sound methods and boost user confidence in results.

Despite some limitations of existing carbon calculators, they nonetheless provide an important public service in educating individuals and guiding them toward responsible behaviors. Those that account for food consumption raise awareness that food consumption should not be overlooked as an indirect contributor to climate change, provide an important resource for a movement toward more sustainable dietary choices, and can empower consumers to pressure industry to favor more sustainable means of production. Current efforts to quantify GHG emissions from the U.S. food system represent the nascent stages of a broadening field, and as additional research becomes available, tools such as carbon calculators will be called upon to accurately, transparently and effectively

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disseminate current and robust guidance. This study provides a snapshot of available calculators, reporting on how well they are fit for this purpose, while providing a framework for identifying ways to improve these valuable tools in parallel with the advent of more refined means to measure diet-related GHG emissions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolecon.2009.08.017.

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