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Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US

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Abstract This article measures the changes in energy use, blue water footprint, and greenhouse gas (GHG) emissions associated with shifting from current US food consumption patterns to three dietary scenarios, which are based, in part, on the 2010 USDA *Dietary Guidelines* (US Department of Agriculture and US Department of Health and Human Services in Dietary Guidelines for Americans, 2010, 7th edn, US Government Printing Office, Washington, 2010). Amidst the current overweight and obesity epidemic in the USA, the *Dietary Guidelines* provide food and beverage recommendations that are intended to help individuals achieve and maintain healthy weight. The three dietary scenarios we examine include (1) reducing Caloric intake levels to achieve "normal" weight without shifting food mix, (2) switching current food mix to USDA recommended food patterns, without reducing Caloric intake, and (3) reducing Caloric intake levels and shifting current food mix to USDA recommended food patterns, which support healthy weight. This study finds that shifting from the current US diet to dietary Scenario 1 decreases energy use, blue water footprint, and GHG emissions by around 9 %, while shifting to dietary Scenario 2 increases energy use by 43 %, blue water footprint by 16 %, and GHG emissions by 11 %. Shifting to dietary Scenario 3, which accounts for both reduced Caloric intake and a shift to the USDA recommended food mix, increases energy use by 38 %, blue water footprint by 10 %, and GHG emissions by 6 %. These perhaps counterintuitive results are primarily due to USDA recommendations for greater Caloric intake of fruits, vegetables, dairy, and fish/seafood, which have relatively high resource use and emissions per Calorie.

Keywords Energy use · Blue water footprint · GHG emissions · Food consumption · Diet

1 Introduction

Most media discourse surrounding overweight and obesity tends to focus exclusively on human health and healthcare costs (Thompson et al. 1999, 2001; Dixon 2010). However, there is a growing recognition that dietary behaviors associated with overweight and obesity have environmental effects in addition to health implications. As a sign of this growing recognition, the US Dietary Guidelines Advisory Committee (DGAC) has recommended for the first time that sustainability should be an integral part of developing the *Dietary Guidelines for Americans* (Merrigan et al. 2015), which are published by the US Department of Agriculture (USDA) and US Department of Health and Human Services every 5 years. In light of this development and mounting evidence that diet and sustainability are intertwined, our study analyzes the environmental implications that food consumption patterns contributing to extra body weight and diet-related diseases have on energy use, blue water footprint, and greenhouse gas (GHG) emissions in the US food supply system. Furthermore,

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while Heller and Keoleian (2014) have evaluated the GHG emissions impact of adopting the USDA recommended diet, our analysis is the first to examine the multiple effects that shifting to the USDA dietary recommendations has on energy use, blue water footprint, and GHG emissions. The blue water footprint refers to the volume of freshwater taken from the surface or ground to create a product, and which has then evaporated, been incorporated into the product, or been returned to a separate catchment from which it was originally withdrawn (Hoekstra et al. 2011).

Heller and Keoleian (2014) determined that shifting from our current average diet to the USDA recommended diet (for a population engaged in moderate physical activity) could reduce GHG emissions within the food supply chain by 1 %. However, they also find that shifting food mix alone without accounting for decreased Caloric intake could increase diet-related GHG emissions by 12 %. While our study also examines the impact on emissions of shifting to the USDA dietary recommendations, we assume different Caloric intake levels and include only adults in our analysis. Further explanation is provided in subsequent sections. In another study similar to ours, Meier and Christen (2013) determine that, in Germany, switching from current dietary patterns to the German Nutrition Society dietary recommendations could reduce energy use by 7 %, blue water use by 26 %, GHG emissions by 11 %, and land use by 15 %. Meanwhile, Vanham et al. (2013a) find that adopting these same dietary guidelines in the entire European Union (EU) and Croatia would reduce their diet-related water footprint by 23 %.

Additionally, a number of studies investigate the impacts of various other diets on the environment. Vanham et al. (2013a), for example, find that the EU and Croatia as a whole could reduce their total diet-related water footprint by 30 % if they reduced their meat consumption by half or by 38 % if they adopted a vegetarian diet. In another similar study, Vanham et al. (2013b) evaluate the water footprint for three diets—current, healthy (based on regional Food-Based Dietary Guidelines), and vegetarian—in four regions of the EU and determine that transitioning to either the healthy diet or a vegetarian diet substantially reduces the total water footprint in all regions. Meanwhile, Vanham and Bidoglio (2014) examine the impact of these same diets on the water footprint of agricultural products in 365 European river basins and determine that shifting to the healthy or vegetarian diet would reduce the water footprint in most of the basins. Marlow et al. (2009) find that in California, a non-vegetarian diet requires 2.9 times more water, 2.5 times more primary energy, 13 times more fertilizer, and 1.4 times more pesticides than a vegetarian diet. Meanwhile, Renault and Wallender (2000) assess several diets, also within the

context of food production in California, and determine that the vegetarian diet yields the greatest results—adopting a vegetarian diet cuts diet-related water consumption by over half.

Tilman and Clark (2014) find that current global dietary shifts toward Calorie-dense foods have not only led to enhanced levels of obesity and diet-related non-communicable diseases around the world, but have also increased agricultural land use and clearing and increased global GHG emissions. They also estimate that by the year 2050, food production emissions will increase 80 % if current dietary trends continue. Conversely, large-scale shifts toward Mediterranean, pescetarian, and vegetarian diets could potentially reduce global agricultural emissions and land clearing by 2050. Eshel and Martin (2006) determine that an omnivorous diet produces approximately 1500 kg CO_2-eq more than a vegetarian diet incorporating the same number of Calories. Likewise, Weber and Matthews (2008) find that replacing less than 1 day's worth of red meat and dairy Calories per week with chicken, fish, eggs, or vegetables is more effective in reducing GHG emissions than buying all food that is locally produced for 1 week.

Our study contributes to the existing literature by providing further insight and analysis to the environmental costs that various dietary choices have on the food supply system in the USA. While there are many environmental impacts associated with food consumption and dietary patterns, we chose to focus on energy use, the blue water footprint, and GHG emissions in light of their accessibility, both in terms of data availability of these impacts for a wide range of food products as well as their relative significance to researchers, policymakers, and the general public. Furthermore, to the best of our knowledge, this article is the first to measure the changes in energy use, blue water footprint, and GHG emissions associated with shifting from current consumption patterns to three dietary scenarios, which are based, in part, on the 2010 USDA *Dietary Guidelines*. The three dietary scenarios include (1) reducing Caloric intake levels to achieve "normal" weight without shifting food mix, (2) shifting food mix to food patterns recommended by the USDA *Dietary Guidelines*, without reducing Caloric intake, and (3) reducing Caloric intake levels and shifting food mix to meet USDA *Dietary Guidelines* in order to achieve and maintain healthy weight.

Our analysis uses a bottom-up approach based on a meta-analysis of the existing academic literature and scientific reports to quantify the cumulative energy use, blue water footprint, and GHG emissions throughout the food supply chain associated with the three aforementioned dietary scenarios. The next sections present the methods and data used followed by a summary of the results and a discussion of the results.

2 Methods and data

The method used is comprised of three main parts: population size, Calories consumed (including food losses) per person, and the life cycle energy use, blue water footprint, and GHG emissions associated with each Calorie.

The basic formulation for our analysis then follows as:

Resource Use and Emissions$_{(A,R)}$

$$= \sum_{i}^{n} \text{adult population} * \left(\frac{\text{Calories}}{\text{Person}}\right)_{i_{(A,R)}} * \left(\frac{\text{Impact}}{\text{Calorie}}\right)_{i_{(A,R)}} \tag{1}$$

where Resource Use and Emissions represent food-related energy use, blue water footprint, and GHG emissions associated with actual (A) and recommended (R) Calories consumed within each food group, i, by American adults, age 19 plus. For our study, actual Caloric consumption (or actual Calories consumed) refers to the sum of actual Calories eaten (or the actual Caloric intake) plus the associated Calories lost through retail-level and consumer-level food losses. Recommended Caloric consumption (or recommended Calories consumed) refers to the sum of the recommended number of Calories that should be eaten (or the recommended Caloric intake) plus the associated Calories lost through retail-level and consumer-level food losses.

Children and teens are excluded from this analysis since the criteria for establishing weight categories and thus actual and recommended Caloric intakes differ from those of adults (Centers for Disease Control and Prevention 2015a). Population data are retrieved from the US Census Bureau, which categorizes individuals by demographics, including by age group (US Census Bureau 2013). In 2010, the US adult population was roughly 230 million people.

2.1 Calories per person

According to the USDA Economic Research Service (ERS) loss-adjusted food availability (LAFA) data series, Americans eat, on average, 2547 Calories daily (US Department of Agriculture 2014). The USDA, however, states that despite the current obesity epidemic, this Calorie amount is high and unrealistic (Buzby et al. 2014). If the average person ate 2547 Calories per day, his/her weight gain over a year or lifetime would be unbelievable and unsustainable (Buzby et al. 2014). For our analysis, we therefore rely on our estimates for actual and recommended Caloric intake levels, which are discussed below.

In 2010, the USDA published their most recent *Dietary Guidelines for Americans*, which help individuals choose healthy eating patterns (US Department of Agriculture and US Department of Health and Human Services 2010).

Amidst the current overweight and obesity epidemic in the USA, the *Dietary Guidelines* provide food and beverage recommendations that are intended to help individuals achieve and maintain healthy weight. More specifically, these guidelines provide a benchmark food density chart, which displays recommended daily intake of each food group for a range of daily Caloric intake needs. Furthermore, the *Dietary Guidelines* categorize the average actual daily intake (per 2000 Calories) in the USA from 2007 to 2010 by food group and by age group (US Department of Agriculture and US Department of Health and Human Services 2010). Daily Caloric intake (actual and recommended) is a function of resting energy expenditure (REE) and physical activity (Lieberman and Marks 2012). REE is the amount of energy in the form of food Calories, or Caloric intake, that is required to support 24 h of normal metabolic functions at rest, including heartbeat, breathing, and body temperature (Lieberman and Marks 2012). Numerous predictive equations for REE have been developed, with subsequent studies examining the validity of many of these equations. Eight of these equations, which were found to be more accurate in predicting REEs, were selected for use in this analysis (Weijs 2008). Table 1 displays relevant information for these eight REE predictive equations.

Anthropometric parameters for the REE predictive equations along with physical activity data were retrieved from the Centers for Disease Control (CDC) National Health and Nutrition Examination Survey, which interviews and examines thousands of respondents in the USA each year (CDC 2014). Actual Caloric intake estimates were determined by using the actual body weight of NHANES respondents as the *weight* parameter in the REE equations. Recommended Caloric intake estimates were determined by replacing the actual weight of NHANES respondents with their calculated maximum healthy or "normal" weight (MNW), which is estimated as:

$$\text{MNW}_i = \text{BMI} \times (H_i)^2 \tag{2}$$

where BMI is body mass index, a measure of body fat, and is set to 25, the overweight threshold, and H is height in meters for each survey participant, i (CDC 2015b). The average of the eight REE estimates was used to determine average actual and recommended Caloric intake amounts for each respondent. Sample weights developed by the CDC were then applied to each value to determine actual and recommended Caloric intake estimates for the average American adult. Refer to Section 1.1.1 of the Supplementary Online Information for additional details in calculating current and recommended Caloric intake.

In 2010, we determined that adults ate, on average, 2390 Calories per day, which is approximately 200 Calories more than what is recommended (based on our calculations) to

Table 1 Selected REE predictive equation studies

References	Parameters	RMSE[a] (Calories/day)
Mifflin et al. (1990)	Weight, height, age, gender	136
Harris and Benedict (1919)	Weight, height, age, gender	148
Roza and Shizgal (1984)	Weight, height, age, gender	151
Schofield (1985)	Weight, age, gender	156
Owen et al. (1986, 1987)	Weight, gender	174
Müller et al. (2004)	Weight, age, gender	139
Henry (2005)	Weight, age, gender	144
Livingston and Kohlstadt (2005)	Weight, age, gender	139

[a] RMSE is root-mean-squared prediction error. Weijs (2008) evaluated the accuracy of 29 REE predictive equations based on bias, RMSE, and percentage accurate prediction. Eight of these equations, which yielded higher accuracy scores, were selected for use in this study

maintain "normal" or healthy weight given the physical activity level of the average American adult. Our estimates for actual and recommended Caloric intake levels are detailed in Section 1.1.2 of the Supplementary Online Information.

Additionally, we incorporate food losses at the retail and consumer levels into our analysis. Although food losses do not contribute to unhealthy eating, they contribute to the overall environmental impacts associated with purchased food, which is directly related to food that is eaten. Food loss estimates based on the LAFA data series (US Department of Agriculture 2014) are retrieved from a USDA report by Buzby et al. (2014), which provides a best estimate of the percentage of Calories within each food group that are lost at the retail and consumer levels in 2010. Based on these percentages, we determine that in 2010, American adults consumed, on average, around 3620 Calories daily, with around 34 % of the total Calories attributed to retail- and consumer-level food losses. It is important to note that while efforts are underway to improve food loss estimates, the USDA Economic Research Service (ERS) still considers their food loss data to be preliminary, particularly at the retail and consumer levels. However, to our knowledge, this information is the best that is available at this time. Refer to Section 1.1.2 of the Supplementary Online Information for detailed estimates of food losses and total food consumed in the USA in 2010.

Figure 1 displays the daily shifts in Caloric consumption of each food group from the current US diet to three dietary scenarios. The first scenario accounts for a reduction in Caloric intake needed to achieve "normal" weight, but maintains our current food mix. The second and third scenarios follow the *Dietary Guidelines* for recommended food mix. But the second scenario does not account for a reduction in Caloric intake, while the third scenario does. The average current Caloric consumption per American adult is around 3620 Calories. Average recommended

Caloric consumption values are estimated as 3300 Calories for scenario 1, 3560 Calories for scenario 2, and 3260 Calories for scenario 3. Although the first and third scenarios account for the same reduction in Caloric intake, Caloric consumption estimates differ due to different food mixes, which yield separate food loss values.

2.2 Energy use, blue water footprint, and GHG emissions per calorie

Following Heller and Keoleian (2014), we conducted a meta-analysis of data published in a variety of government reports and scientific literature to determine ranges of life cycle energy use and blue water footprint per Calorie consumed of each food type. We retrieved most of our blue water footprint data from two Mekonnen and Hoekstra (2011, 2012) studies, which provide comprehensive water footprint data for over 400 foods produced in the USA and worldwide. In addition, we incorporated GHG emissions data from Heller and Keoleian. We drew our food-related resource use and emissions estimates from life cycle assessment studies conducted in primarily advanced industrialized countries. Various climates, transport modes and distances, food-related technology, and production methods are reflected among the data compiled. We therefore average the resource use and emission intensity estimates found for each food type and use these average values in our analysis. Furthermore, we list the minimum and maximum resource use and emissions estimates found in the literature to provide intensity ranges for each food type. Refer to Section 1.2 of the Supplementary Online Information for detailed results of our meta-analysis of resource use and emissions factors for 100 plus food types.

Figure 2 displays index scores for energy use, blue water footprint, and GHG emissions through the food supply system required to produce and consume one Calorie of each food group. Fruits and fish/seafood have the highest average energy use index values, fruits yield the

Fig. 1 Shifts in average daily Caloric consumption per adult from the current US diet to three dietary scenarios. Positive values represent an increase in Caloric consumption from our current diet to a recommended diet, while negative values represent a decrease in Caloric consumption from our current diet to a recommended diet
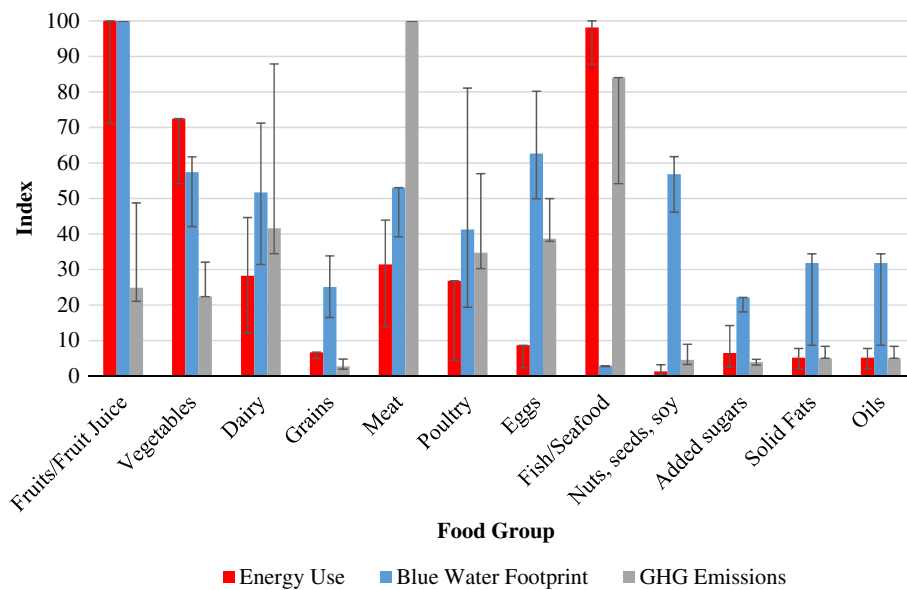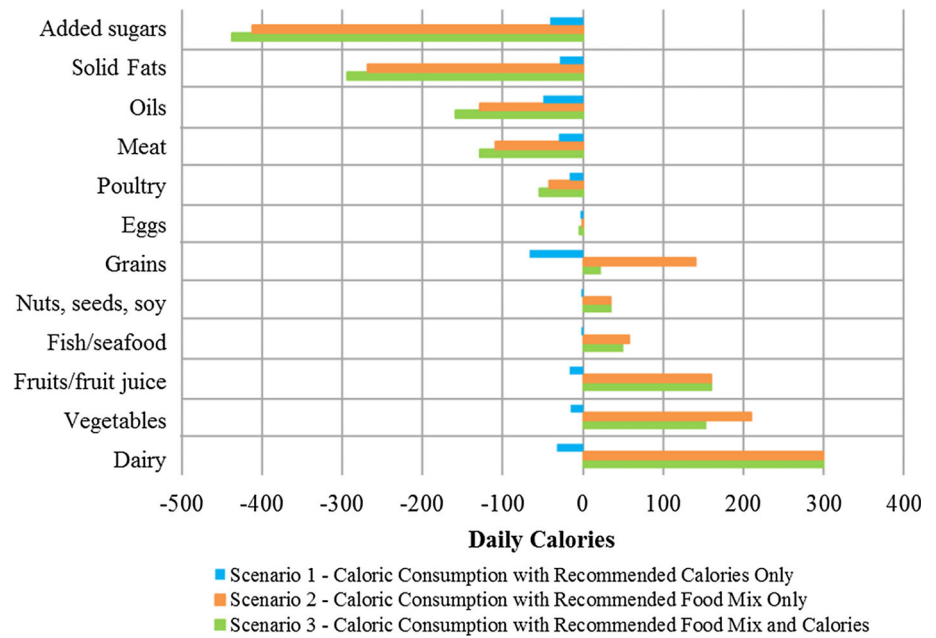

Fig. 2 Indices of average energy use, blue water footprint, and GHG emissions per Calorie of food for each food group. An index score of 100 represents the highest resource use and emissions per Calorie. Scores were developed based on the weighted averages of energy use, blue water footprint, and GHG emissions per Calorie estimates for comparable food types within each food group. *Whiskers* the range of scores based on the minimum intensity values for all food types and the maximum intensity values for all food types. Refer to Section 1.2 of the Supplementary Online Information for intensity factors for all 100 plus food types used in this analysis (Color figure online)

highest index score for blue water footprint, and meats and fish/seafood have the highest average GHG emissions index values. While energy use intensities for fruit production vary significantly depending on location and production methods, fruits, on average, have the highest energy index score, primarily because they have low-Calorie densities relative to other foods. Meanwhile, fish/seafood has the second highest energy use and GHG

emissions intensities due to a variety of factors. For farmed fish, this is largely due to feed production, as fisheries and farms that produce the feed ingredients are often energy intensive. Specifically, for farmed Salmon, feed production accounts for 93 % of the cumulative energy use from farm to farm gate (Pelletier et al. 2009). Furthermore, with regard to wild-caught fish, energy intensity of fishing activity is the main contributor toward the high energy use

for fish and seafood (Foster et al. 2006). In particular, fishing vessels are fuel intensive, resulting in high GHG emissions, especially if they have to travel far away from where they are stationed to find higher concentrations of fish (Svanes et al. 2011).

Meanwhile, fruits have the highest blue water footprint index score because (1) fruits have, in general, low-Calorie density compared to other food types and (2) a large portion of our fruits are grown in California, which has a naturally dry climate, thereby requiring large volumes of irrigation. This increases the overall US-based blue water intensities for fruit used in this analysis since these unit values are weighted, in part, by the amount of fruit produced in each state. Red meat attains the highest index score for GHG emissions, mainly due to methane emissions from enteric fermentation and nitrous oxide from excreted nitrogen as well as from fertilizers used to produce animal feed (United Nations Environment Programme 2012). Conversely, oils and grains as well as nuts, seeds, and soy have the lowest energy index scores, with grains having the lowest GHG emissions index value. Meanwhile, fish and seafood rank lowest for blue water footprint.

3 Results

Figure 3a displays the average annual energy use, blue water footprint, and GHG emissions associated with the current average diet of American adults and with the three dietary scenarios, which are based, in part, on the USDA *Dietary Guidelines*. It is important to note that all values include consumer and retail-level food losses. As shown in Fig. 3b, a shift to a diet with the recommended Caloric intake reduces energy use, blue water footprint, and GHG emissions, by around 9 %, on average, while a shift to a diet with the recommended food mix increases average energy use by 43 %, the average blue water footprint by 16 %, and average GHG emissions by 11 %. Shifting to the recommended dietary scenario that accounts for both reduced Caloric intake and a shift to the USDA recommended food mix increases average energy use by 38 %, the average blue water footprint by 10 %, and average GHG emissions by 6 %.
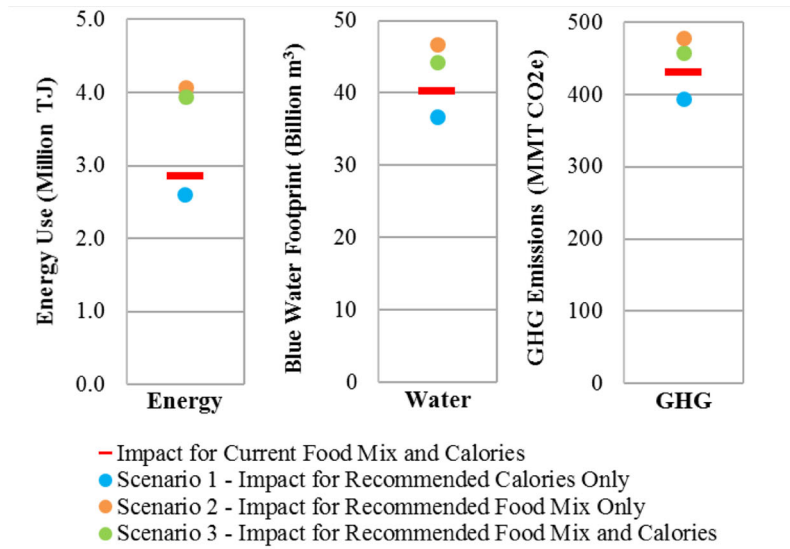
Additionally, we conduct a sensitivity analysis using the minimum and maximum resource use and emission intensity values for each food product in our meta-analysis to develop low and high scenarios, respectively, for our results. We also account for potential variability in food loss estimates. According to Buzby et al. (2014), food loss values are likely underestimated by the USDA. Based on their food availability data and our Caloric intake estimates, we determine that retail- and consumer-level food

losses could exceed 37 %. Moreover, in a preliminary report, Lipinski et al. (2013) estimate that in North America and Oceania, food losses throughout the entire food supply chain are approximately 42 %. However, they do not report the distribution of these losses to each food group. For our sensitivity analysis, we therefore establish an upper bound of 42 % for food losses and distribute these losses among the food groups in the same proportion as in our original analysis. To the best of our knowledge, no studies report food losses in the USA below 34 %, which is the value provided by the USDA for retail- and consumer-level losses, and which we use in our study. Thus, our original food loss estimate of 34 % establishes the lower bound value for our sensitivity analysis, which is displayed in Fig. 4a–c.
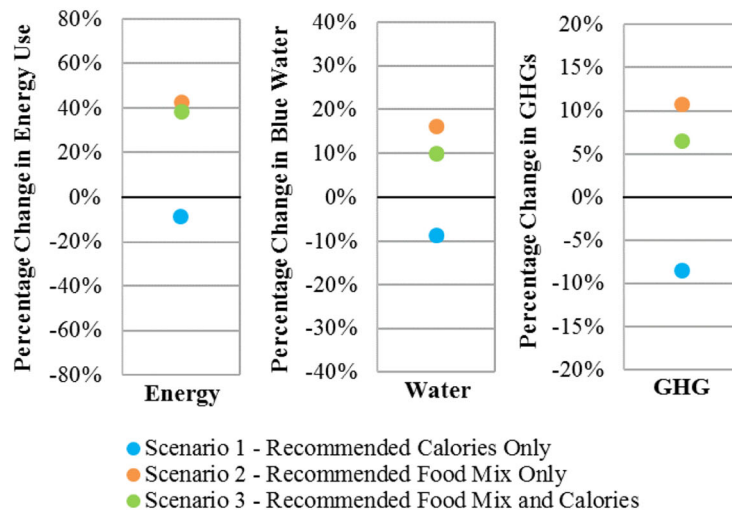
It is perhaps especially surprising that cumulative energy use, the blue water footprint, and GHG emissions all increase under Scenario 3, which, in addition to a shift in food mix, also accounts for a 9 % reduction in Caloric consumption. Despite this Calorie reduction, cumulative energy use increases by 0.4 million TJ (using lower bound estimates) to 3.4 million TJ (using upper bound estimates), which represents an increase of 33–51 %. Under dietary Scenario 2, which accounts for a shift in food mix only, energy use increases by 0.5 million TJ (using lower bound estimates) to 4.2 million TJ (using upper bound estimates), which corresponds to a 41–62 % increase from current consumption patterns. These results demonstrate that the USDA recommended food mix has a far greater impact on our Scenario 3 outcome than reducing Caloric intake. In particular, we find that increased energy use is primarily due to USDA recommendations for higher consumption of fruits (Fig. 1), which among all food groups represent the greatest cumulative energy use per Calorie (Fig. 2). Vegetables, which have the third greatest energy intensity value, have the second most contributing influence on increased energy use, behind fruits. Although fish/seafood has a higher average energy intensity than vegetables, the impact of vegetables is compounded by a significantly greater increase in recommended consumption, as shown in Fig. 1. Furthermore, although the USDA recommended diet requires substantial decreases in sugars, fats, and oils, these foods require significantly less cumulative energy use per Calorie.

The blue water footprint decreases by 9 % under Scenario 1, while the lower bound estimate for current water use increases by 28 and 22 % under Scenarios 2 and 3, respectively, and the current upper bound estimate increases by 16 and 8 % under Scenarios 2 and 3, respectively. Again, the main driving force behind our results for Scenario 3 is the recommended shift in food mix. More specifically, the increased blue water footprint is mainly due to increased quantities of fruits, which, on

Fig. 3 Average energy use, blue water footprint, and GHG emissions through the food supply chain. **a** The average annual energy use, blue water footprint, and GHG emissions required to support the current diet of the US adult population as well as the three recommended dietary scenarios. The *red lines* represent the food-related impacts associated with our current diet, while the dots correspond to the annual impacts associated with the three dietary scenarios. **b** The shifts in energy use, blue water footprint, and GHG emissions from our current diet to the three recommended diets (Color figure online)

— Impact for Current Food Mix and Calories
● Scenario 1 - Impact for Recommended Calories Only
● Scenario 2 - Impact for Recommended Food Mix Only
● Scenario 3 - Impact for Recommended Food Mix and Calories

(a) Total annual energy use, blue water footprint, and GHG emissions

● Scenario 1 - Recommended Calories Only
● Scenario 2 - Recommended Food Mix Only
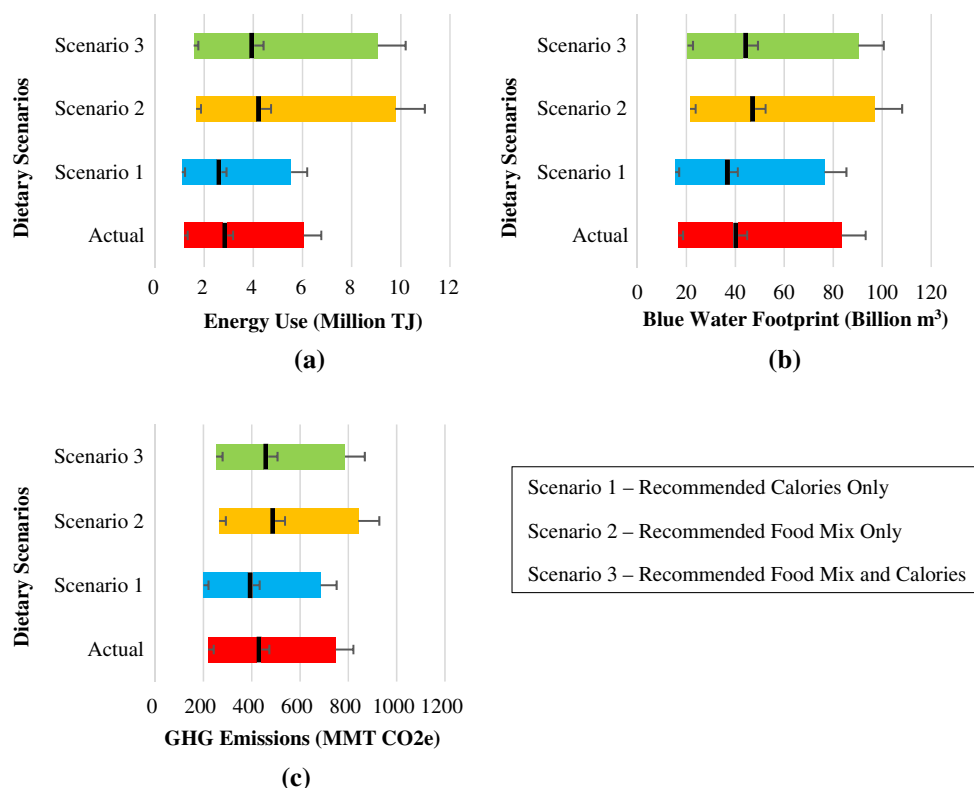● Scenario 3 - Recommended Food Mix and Calories

(b) Percentage change in energy use, blue water footprint, and GHG emissions

average, require the greatest amount of irrigation per Calorie. Recommended increases in vegetables and dairy products are the second and third greatest contributing factors, behind fruits, that drive the increased blue water footprint in Scenario 3. Although eggs and nuts are the third and fourth most water-intensive foods per Calorie as shown in Fig. 2, the recommended shifts in these foods are quite small relative to the considerable increases in dairy and vegetables, demonstrated in Fig. 1. Furthermore, despite significant decreases in Caloric consumption of sugars, fats, and oils, these foods have relatively low blue water footprints per Calorie.

Lastly, GHG emissions increase despite reduction in Calories and a shift to the USDA recommended food mix, which lowers red meat consumption. Although meat

products have the highest emissions per Calorie, overall GHG emissions increase due to increased Caloric intake of dairy, seafood, fruits, and vegetables, which collectively offset emission reductions resulting from decreased meat consumption as well as reduced sugars, fats, and oils, which again have relatively low emissions per Calorie. Dairy, by far, has the greatest impact on increased GHG emissions because it has the third highest emissions intensity value, which is then compounded by USDA recommendations for substantial increases in dairy. Fish/seafood is the second most driving force behind increased GHG emissions. While recommended intake of fish/seafood is low relative to fruits and vegetables, the emission intensity of fish/seafood is significantly higher. Nonetheless, fruits and vegetables are still a contributing factor

Fig. 4 Range of annual cumulative energy use, blue water footprint, and GHG emissions through the food supply chain. **a–c** The ranges of annual energy use, blue water footprint, and GHG emissions required to support the current diet of the US adult population as well as the three recommended dietary scenarios. The *vertical black lines* represent the average estimates, which correspond to the impact values displayed in Fig. 3a. The *whiskers* represent the range of values for the lower bound, upper bound, and average impacts that are attributed to variability in food losses (34–42 % food losses). **a** Range of total annual energy use. **b** Range of total annual blue water footprint. **c** Range of total annual GHG emissions (Color figure online)

(a) Energy Use (Million TJ)

(b) Blue Water Footprint (Billion m³)

(c) GHG Emissions (MMT CO2e)

Scenario 1 – Recommended Calories Only

Scenario 2 – Recommended Food Mix Only

Scenario 3 – Recommended Food Mix and Calories

toward increased GHG emissions, primarily due to greater intake of these foods, per USDA recommendations. Finally, while the recommended reduction in Calories is mainly attributable to lower consumption of sugars, fats, and oils, these food products have very low resource use and emissions per Calorie and are therefore insufficient in reducing overall resource use and emissions associated with shifts toward the USDA *Dietary Guidelines*.

It is also important to note that increasing food losses from 34 to 42 % increases the overall energy use, blue water footprint, and GHG emissions by approximately, 12 % for both current and recommended food consumption scenarios. However, this shift in food loss estimates does not alter the percentage change in resource use and emissions from current to recommended scenarios. This is because while we account for differences in overall food loss estimates, we maintain the same proportion of food loss across each of the food groups.

4 Discussion

In light of the obesity epidemic in America, there have been recent efforts to promote healthy eating habits through reducing Caloric intake and encouraging healthier dietary choices. This movement has led to the emergence of a body of scholarship investigating the relationships between food consumption and environmental sustainability. The present study advances the debate further by utilizing a more nuanced measure of food consumption to demonstrate that healthy dietary changes can have negative implications for environmental sustainability, thus illustrating an example of tension between public health and environmental sustainability. In addition, this study's results demonstrate how the environmental benefits of reduced meat consumption may be offset by increased consumption of other relatively high impact foods, thereby challenging the notion that reducing meat consumption automatically reduces the environmental footprints of one's diet. As our results show food consumption behaviors are more complex, and the outcomes more nuanced.

While it is feasible to achieve normal weight by reducing Calories without shifting food mix (Freedman et al. 2001), it is beneficial from a human health perspective to consider both factors. As shown here, from an environmental standpoint, it is also important to consider both the source of our Calories and the amount of Calories we consume. As our study demonstrates reducing Calories alone to achieve normal weight could reduce energy use, blue water footprint, and GHG emissions for adults by as much as 9 %, assuming that food supply follows reduced demand. However, when considering both Caloric reduction and a dietary shift to the USDA recommended food mix, average energy use increases 38 %, average blue

water footprint increases 10 %, and average GHG emissions increase 6 %. These results represent an increase of roughly 1 % of the total national annual energy budget, 7 % of total US blue water footprint, and 0.5 % of total US GHG emissions for all sectors. Based on our upper bound estimates, these values increase to 3, 12, and 1 %, respectively. These findings provide reasons for decision makers to consider both the nutritional value and environmental implications of food choices when developing dietary recommendations.

4.1 Comparisons with other studies

As noted above, there is a robust and ever-growing literature on this subject. Heller and Keoleian's results for GHG emissions associated with shifts to dietary recommendations differ from the estimates found here. Heller and Keoleian (2014) find that shifting food mix without reducing Calories yields a 12 % increase in diet-related GHG emissions, while accounting for both food mix and Calorie reduction leads to a 1 % decrease in emissions. We, however, determine that on average, shifting to the USDA recommended food mix alone yields a 11 % increase in food-related GHG emissions for American adults, while shifting food mix and reducing Calories result in a 6 % increase in GHG emissions. Their results differ from our estimates, in part because their findings are based on Caloric intake estimates, whereas the results found in our analysis are based on Caloric consumption estimates, which include retail- and consumer-level food losses. We include food losses in our estimates because they contribute to the overall environmental impacts associated with food choices. Furthermore, Heller and Keoleian assume a reduction in Calories from current Caloric intake (based on the LAFA data series) to recommended Caloric intake (for the average American, including children, assuming moderate physical activity) that is more than twice our reduction estimates. Despite this significant Caloric reduction, the difference between our results and those of Heller and Keoleian is relatively small, which further indicates that food mix plays a greater role than overall Caloric intake in determining the results of this study.

Meier and Christen (2013) determine that an iso-Caloric shift to the German Nutrition Society official food-based dietary recommendations could reduce energy use by 7 %, blue water use by 26 %, emissions by 11 %, and land use by 15 %. These findings differ significantly from our increased impact estimates resulting from an iso-Caloric shift to the USDA *Dietary Guidelines*. Meier and Christen's study accounts for larger reductions in meat, poultry, and egg consumption and smaller increases in vegetable and dairy products. Their analysis also accounts for reduced fruit consumption, whereas the USDA recommends that the portion of the US current Caloric intake

attributable to fruit intake be increased by nearly 85 %. Furthermore, contrary to our dietary recommendations, the German Nutrition Society suggests a slight increase in fats and oils, and a larger increase in grain consumption. These foods, however, have relatively low impacts per Calorie compared to other foods, such as fruits, vegetables, meat, poultry, and eggs. Hence, the interplay between consumption patterns and dietary recommendations of different nations, as well as regional differences in agricultural production explains the differences between our results and those of Meier and Christen.

In comparison, Vanham et al. (2013a) determine that shifting to these same German dietary guidelines within the EU and Croatia while also accounting for a reduction in Caloric intake would reduce their diet-related blue water footprint by 18 %, which is significantly different from the results of our study (increase of 10 %). While their recommended Caloric intake amount is similar to ours, their actual intake estimates are significantly higher, thereby leading to a decrease in overall Caloric intake that is more than three times greater than our estimated reduction. This is due, in part, to their inclusion of alcoholic beverages and spices, which are omitted from this analysis. Furthermore, the increased blue water footprint results found in our study are primarily driven by substantial increases in fruits, vegetables, and dairy. While the EU is also encouraged to increase their intake of these foods under the dietary guidelines of the German Nutrition Society, their recommended increases are significantly lower—i.e., 20 versus 96 more fruit Calories capita^{-1} day^{-1}, 33 versus 104 more vegetable Calories capita^{-1} day^{-1}, and 11 versus 204 more dairy Calories capita^{-1} day^{-1}. Also, unlike the USDA guidelines, which recommend greater intake of nuts and seeds in the USA, the German Nutrition Society gives no recommendation for this food group. Thus, Vanham et al. (2013a) assume no change in the intake of nuts and seeds, which have relatively high blue water intensities in the USA.

Vanham et al. (2013b) examine the impact that shifting to a healthy diet based on regional Food-Based Dietary Guidelines has on the water footprint in four EU zones. They find that adopting a healthier diet decreases the blue water footprint by 4, 18, and 26 % in three regions and increases the blue water footprint by roughly 4 % in the fourth region, the NORTH region. These estimates differ significantly from one another as well as from estimates found here. In the NORTH though, the blue water footprint increases from the current to the healthy diet due to higher intake of fruits, which require more irrigation. This component of the results is consistent with our findings. Meanwhile, Vanham and Bidoglio (2014) conduct a similar study, evaluating the impact that shifting to a healthy diet based on regional Food-Based Dietary Guidelines has on 365 European water basins. They determine that under the

healthy diet scenario, the blue water footprint decreases for the majority of river basins, with the exception of some Eastern or Northern European basins, which have higher meat intake recommendations. Our findings, which reveal an increase in the blue water footprint when shifting to a healthier diet, contrast with those of Vanham and Bidoglio. However, further research is needed to reconcile these differences.

Additionally, in light of the growing evidence that meat production has negative environmental implications, a number of studies including the aforementioned analyses examine the impacts of reducing meat consumption on resource use and emissions through the food supply system. The results of these studies (Heller and Keoleian 2014; Vanham et al. 2013a, b; Renault and Wallender 2000; Marlow et al. 2009) demonstrate that adopting a vegetarian diet or even reducing meat consumption by 50 % is more effective in reducing energy use, the blue water footprint, and GHG emissions through the food supply system than adopting a healthier diet based on regional dietary guidelines.

4.2 Limitations and future work

Resource use and emissions data for each food type evaluated in our study were collected from various environmental life cycle assessment (LCA) studies, many of which were conducted in other developed countries. A major limitation of our study, thus, stems from this meta-analysis approach. For instance, differences in geography, climate, and culture may warrant different food production methods and resource requirements. Also, system boundaries and allocation methods differ among LCAs (Heller and Keoleian 2014). We therefore report minimum and maximum environmental intensities for each food type in the Supplementary Online Information to demonstrate the potential range of resource use and emission factors. A preliminary sensitivity analysis was then conducted using the minimum environmental intensity parameters of all foods to develop lower bound scenarios for the results, while maximum intensity values were used to develop upper bound scenarios—thus, establishing a range of potential outcomes. While this is a first step toward analyzing the uncertainty of our results, a more robust analysis is needed in future work to evaluate the effects of different resource use and emissions intensity mixes on the overall range of results. In addition, more extensive analyses of US-based LCAs for food products are also needed to better substantiate our findings.

Additionally, the 100 plus food types accounted for in our study are based on those listed in the LAFA data series. Although these foods represent raw or semi-processed agricultural goods (Heller and Keoleian 2014), we include

a significant number of final retail products in our analysis and categorize them according to the food types listed by LAFA. The majority of LCAs for final retail products evaluated in this study include all phases of the food supply chain, including retail and household. However, due to lack of "farm to fork" LCA data for some food types, we also incorporate LCAs that have more limited system boundaries (farm to farm gate, etc.). Consequently, energy use, blue water footprint, and GHG emissions may be omitted from various stages of the food supply system for certain food products, which could lead to underestimated results. Current literature, however, lacks LCA data for the wide array of food products purchased and consumed in the USA. We attempt to address this issue by estimating a range of resource use and emission outcomes based on minimum and maximum intensity factors and food loss estimates. Thus, we feel that, given the available data, our analysis is the most comprehensive yet in this area.

The sustainability of food production depends on the extent to which production impacts the environmental needs of a region. Specifically, for water use, freshwater availability varies across countries and regions. Withdrawing water from a water-scarce area that is populated has different implications for the environment and for society than withdrawing the same amount of water from a location with greater water resources. While we recognize this to be an important concept in determining blue water footprint impacts, it is beyond the scope of this project to account for water resource availability and water scarcity index factors across different regions of the country. But given that fruits and vegetables are the main contributor to the overall increased blue water footprints in our recommended dietary scenarios, and given that much of our produce is grown in drought stricken California, it would seem that accounting for regional-level food production and applying water scarcity factors across regions would produce impacts that not only align with the direction of our results, but also signify the importance of the overall increased blue water footprint found in this study. Further research, however, is needed to validate this assumption.

This study sheds light on the trade-offs between human and environmental health within the context of dietary choices. Shifting from current consumption patterns to USDA dietary recommendations corresponds to an increase in diet-related energy use, blue water footprint, and GHG emissions among American adults. This perhaps counterintuitive outcome reveals the complex relationship between diet and the environment. While our results are not intended to dissuade healthy eating, they do draw attention to the need for cooperative efforts between policymakers, health officials, and consumers to establish dietary recommendations that meet both health and environmental objectives.

5 Supplementary online information

Additional tables and detailed documentation of methods, numeric data, and calculations regarding energy use, blue water footprint, and GHG emissions attributable to current food consumption patterns and USDA dietary recommendations.

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