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Environmentally Optimal, Nutritionally Aware Beef Replacement Plant-Based Diets

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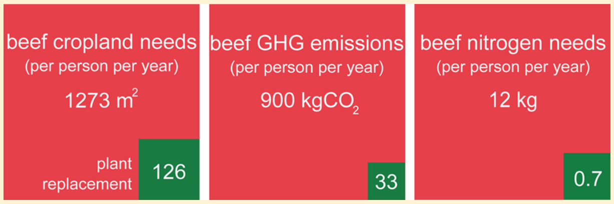
Supporting Information



ABSTRACT: Livestock farming incurs large and varied environmental burdens, dominated by beef. Replacing beef with resource efficient alternatives is thus potentially beneficial, but may conflict with nutritional considerations. Here we show that protein-equivalent plant based alternatives to the beef portion of the mean American diet are readily devisible, and offer mostly improved nutritional profile considering the full lipid profile, key vitamins, minerals, and micronutrients. We then show that replacement diets require on average only 10% of land, 4% of greenhouse gas (GHG) emissions, and 6% of reactive nitrogen (Nr) compared to what the replaced beef diet requires. Applied to 320 million Americans, the beef-to-plant shift can save 91 million cropland acres (and 770 million rangeland acres), 278 million metric ton CO_{2e}, and 3.7 million metric ton Nr annually. These nationwide savings are 27%, 4%, and 32% of the respective national environmental burdens.

INTRODUCTION

While all food production taxes the environment,[1] livestock is disproportionately taxing,[2] and beef exerts by far the most environmental burdens.[3] Conversely, plant foods tend to demand significantly less resources.[4] Consequently, considering the environmental impacts of replacing the ≈190 kcal person^{-1} d^{-1} beef with plant based alternatives is timely. (In "beef", we also include veal and tallow, consistent with our earlier calculations.[3,5] We define the Mean American Diet (MAD[6]) as the 2000−2010 means (again in keeping with our earlier calculations[3,5]) of United Stated Dept. of Agriculture (USDA) data.[7])

Yet such replacement calculations raise a conundrum, best introduced by the example of replacing beef with high fructose corn syrup. Considering only cropland (i.e., discounting pasture as a free resource), under current practices, U.S. beef yields[3] at most 250 Mcal ac^{-1} y^{-1}. By comparison, high fructose corn syrup yields[7] 4200 Mcal ac^{-1} y^{-1}. Nationally replacing the ≈190 kcal beef person^{-1} d^{-1} with corn syrup would thus spare almost 80 million cropland acres, a fifth of the total national cropland acreage.[8] Yet the nutritional profile of high fructose corn syrup, especially its role in promoting Type II diabetes, renders such a shift nutritionally unwise. This highlights the importance of simultaneously considering nutritional *and* environmental impacts of putative dietary shifts,[4,9] and the limitations of energy as the sole basis for comparison.[10] Here, we devise plant based alternatives to beef that minimize resource use while satisfying key nutritional requirements, and quantify the environmental and nutritional corollaries of this shift.

MATERIALS AND METHODS

The calculations on which this paper is based update our earlier papers,[3,5] including updating feed composition based exclusively on NRC data,[11,12] and an updated account of byproducts in livestock feed.

To evaluate plant-based replacement to beef we construct diets comprising combinations of plant items that adequately replace (as described below) the beef portion of the MAD. We devise these varied alternative diets by employing Monte Carlo sampling and linear programming.[4] The starting point of each Monte Carlo realization is the random choice of a set of 60 plant items out of the full list of 65 considered items (enumerated in Supporting Information (SI) Table S1, representing the most commonly used items in the MAD). Randomizing individual realizations by considering different sets of plant items strives to represent day-to-day dietary variability by devising adequately diverse solutions that reflect seasonal and regional availability and varied life circumstances that impact actual dietary choices.

For each combination of 60 plant items, we seek the 60 item-specific masses that jointly replace beef in the MAD, satisfying the following four inequality constraints (SI eq S2). We derive the per capita daily bounds on replacement diets' energy, fat and protein content from beef's contributions to the current loss-adjusted MAD. We set energy to ≤190 kcal d^{-1}, reflecting

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the fact that in the U.S., excess calories are rampant and deleterious while caloric deficit is practically nonexistent. (This bound may be 4% inflated, yet it is necessary to keep it for consistency. This has virtually no impact on this paper, as we discuss in the SI *The Right Hand Side Vector of Bounds*. This is not only because the overestimate is small, but more importantly because what is key to the replacement calculation is the *ratio* of the energy, fat and protein bounds, and much less their absolute values. And since the fat and protein bounds are linear functions of the energy bound, these ratios are conserved under the overestimate.) We set fat content to ≤ 16 g d^{-1}, reflecting the view of primarily saturated animal fats as mostly harmful.[13] Recognizing the often asserted[14] protein insufficiency of plant based diets and the fact that beef is eaten as a protein, not energy source, we set protein to ≥ 11 g d^{-1}. We also constrain daily total mass. Recognizing that most nutritionally desirable plant based diets are bulkier than isocaloric animal based items,[14] this mass upper bound is 131 g, twice the beef mass. This is imposed in addition to individual items' maximum permissible mass (see SI), so that together, with m_i denoting the individual mass of item i), $\Sigma_i m_i \leq 131$ g d^{-1} with $m_i \leq 15$ g d^{-1} for each individual i. This, along with the wide range of caloric density among plant items, ensures daily diets that are reasonably diverse (not dominated by one or two items) and, while bulkier than the replaced beef, are not unrealistically massive.

We randomly choose 500 plant combinations (out of over 8 million options) and for each find the set of 60 item-specific masses that jointly minimize either land use, GHG emission or reactive nitrogen use (Nr; such biologically available nitrogenous compounds as urea or nitrate ion that dominate agricultural water pollutant) while satisfying the four inequality constraints. The average over the 1500 solutions, covering the 500 plant item combinations and three minimizations, yields a mean solution that takes equal note of each of the three considered burdens. For further details of the method see the SI.

The solutions for each viable plant item combination are the consumed masses of the considered 60 plant items that jointly meet the above energy, protein, fat and mass criteria while optimizing one of the environmental outcomes. The constraints thus ensure that macronutrient levels adequately replace beef by falling within recommended ranges,[15] and the minimizations ensure least environmental impacts. The overall solution, the combined statistics of all randomized diets, comprises the masses of all 65 plant items.

For each of the 1500 beef replacement diets, we quantify the environmental and nutritional characteristics in terms of all three environmental metrics, lipid content and composition, other macronutrients, and a range of key vitamins, minerals and other micronutrients (see SI Table S2 for a complete list of evaluated attributes). Repeating the randomizations with 58 and 62 items per realization yield essentially the same results (not shown) as those presented below based on 60 items per diet. For completeness, we provide in the final section of the SI deterministic diets obtained with all 65 plant items available for consideration.

■ RESULTS AND DISCUSSION

Figure 1 presents statistics of the composition of the 1500 randomized, optimized beef replacing plant based diets (showing means calculated over 500 unique plant combination and the three environmental optimizations). Legumes and peanuts dominate the diets, and reassuringly, leading items in these diets, such as peanuts, lentils, or kidney beans, are consistent with straightforward, authoritative nutritional advice.[9,16] Suggesting our replacement diets are also readily deployable, these leading items are well represented in the actual MAD. For example, the average American eats 10 and 40 kcal d^{-1} ($\approx$2.8 and 2.6 kg y^{-1}) kidney beans and peanuts;[6] not dominant but decidedly not negligible. Leading items are also more affordable than beef. For example, while on Nov. 2015 various beef cuts ranged in stores throughout the Midwest and the U.S. as a whole over 4−9 dollars lb^{-1}, the same data show that a lb of dried beans and peanut butter were selling for 1.5 and 3 dollars.[17] Thus, affordable, commonly used, widely available and nutritionally equivalent or better plant items dominate the optimized diets.

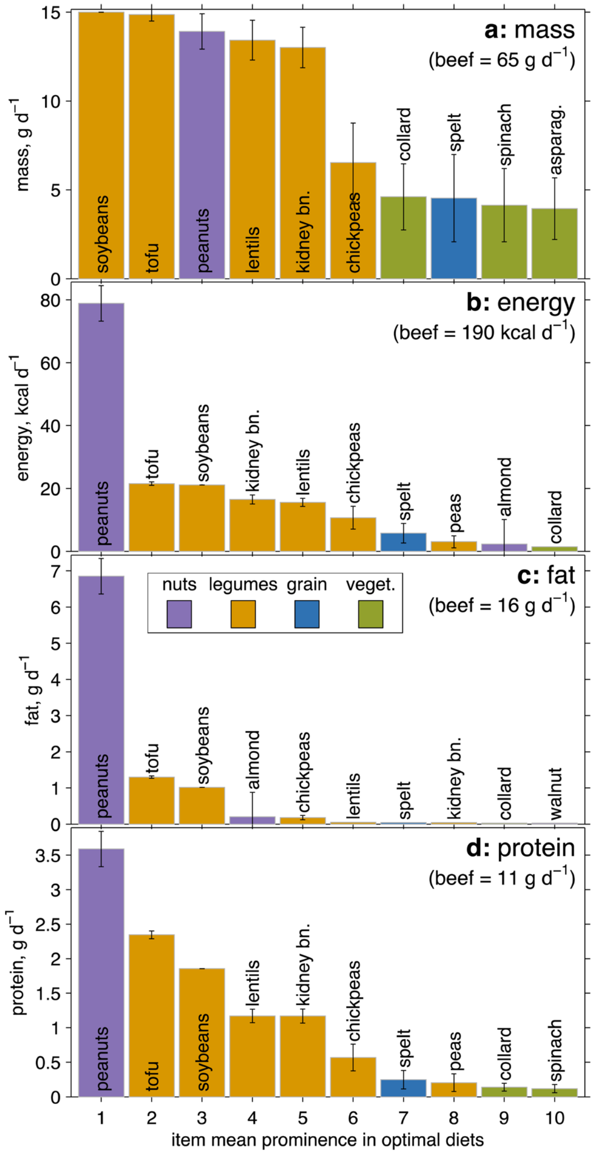

Figure 1. Leading items in the plant based beef replacement diets, ranked by contribution to the metric indicated on the upper right. Bar heights and vertical whiskers show mean ±1 standard deviation calculated over all diets.

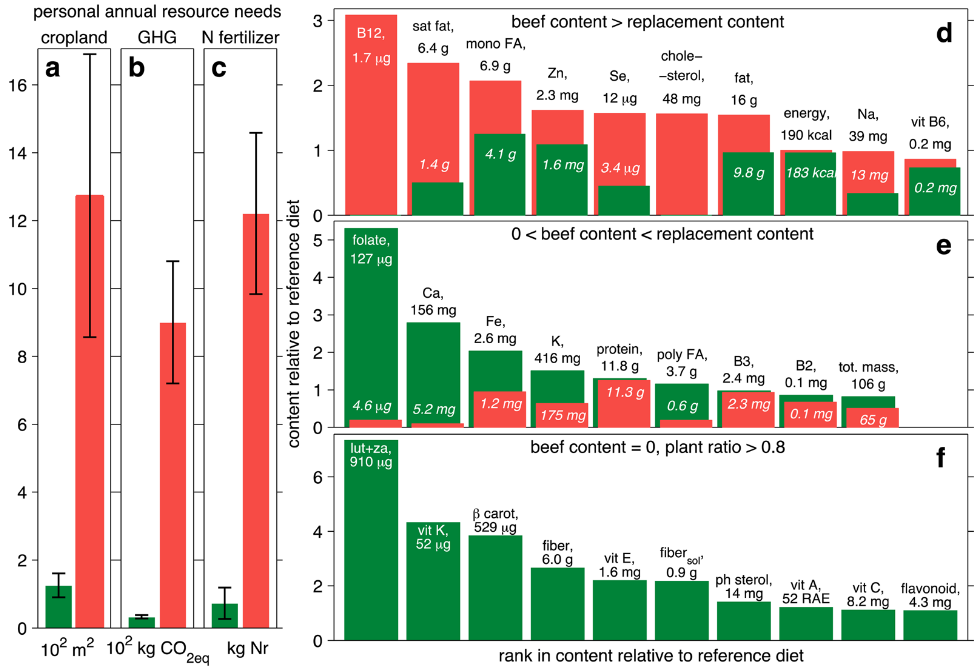

Figure 2. Environmental (a−c) and nutritional (d−f) attributes of the plant based diets (green) replacing the beef portion of the MAD (red). Panels a−c present resource needs (with units indicated below the panels, with whiskers showing ±1 standard deviation calculated over all diets) of the partial replacement diets. Panels d-f express nutritional attributes as ratios relative to a MAD-like reference diet, the mean delivery by randomly chosen 190 kcal subsets of the full MAD (see text for details). Minimally distinct attributes are suppressed. FA = fatty acids; RAE = retinol activity equivalents.

The environmental resources the beef and replacement plant based diets use are compared in Figure 2a-c. Differences in total high quality cropland (Figure 2a; usable for either food or feed production) are enormous, with best estimate ± standard error of 1273 ± 417 and 126 ± 35 m^2 person^{-1} y^{-1} for beef and its plant based replacement diets, a 90% land use reduction. The GHG and Nr differences—901 ± 180 vs 33 ± 5 kg CO2$_{eq}$ person^{-1} y^{-1} and 12 ± 2 vs 0.7 ± 0.5 kg Nr person^{-1} y^{-1} (94−96% reductions)—are even larger (see SI for further details).

The nutrient supply of the replaced and replacement diets are compared in Figure 2d−f. Nutrient supplies are normalized by the supply that a 190 kcal portion of the full MAD (including but not limited to beef) is expected to deliver. For example, a value of 2 along the vertical axis indicates that the considered diet delivers twice as much of the nutrient in question as randomly chosen ≈190 kcal portions of the MAD do.

Figure 2d focuses on nutrients that beef supplies more of than the plant based replacement. Consistent with their well established B_{12} insufficiency,[18] the chosen plant based diets supply no vitamin B_{12}, while the replaced beef supplies 1.7 μg, 71% of the full recommended adult daily intake.[15] Similarly, beef supplies ≈68% more monounsaturated fatty acids, generally regarded as protective.[9,16] Less extreme are zinc and selenium. Of zinc, often popularly invoked as an important dietary contribution of beef, the beef and plant-based alternative diets supply 2.3 and 1.6 mg, or 23% and 16% of the full recommended adult daily intake.[15] For selenium, the values are 12 and 3 μg, ≈24% and 5% of the full recommended adult daily intake.[15] The replacement plant based diets are thus B_{12} and Zn deficient, minimally Se insufficient, and supply less monounsaturated fatty acids. Yet the vitamins and minerals of these deficits are easily ameliorated by supplements (exerting some, unknown but presumably minor, additional environmental burdens). The potentially less protective monounsaturated fat content of the plant diets (4.1 g as compared to 6.9 g from beef) is offset by the added polyunsaturated fatty acids (panel e), of which plants supply 6 times the beef supply. The supply of unsaturated fats in the plant based alternative diet is thus of no nutritional concern.[19] In terms of vitamins B_2 and B_6, the replaced and replacement diets are essentially interchangeable. The remaining nutrients in Figure 2d, of which plants supply significantly less than beef, are generally viewed as harmful[9,16] (but the Na content of both replaced and replacement diets are trivial compared with the daily recommended[15] ≤ 2.3 g).

The remaining nutrients or attributes, of which the beef diet supplies less than the replacement diets (Figure 2e−f), fall into two categories. Most are considered protective,[20,21] rendering replacing beef with plants nutritionally desirable. Possible exceptions may be iron and carbohydrates. Assuming typical composition of the adult population, Fe RDA and upper limit are[15] 11 and 45 mg d^{-1}, translating to 0.9 and 4.0 mg d^{-1} for 190 kcal portions. Thus, the Fe supplies of replaced or replacement diets are acceptable. Finally, the plant diets supply 15 g or 57 kcal carbohydrates daily. While under a third of the 190 kcal total energy, this added carbohydrates (beef supplies none) may still be problematic, if supplied in rapidly digested forms. This concern is largely alleviated by the fact that nearly the full added carbohydrate mass is contributed by slowly digested beans.[9,16]

The presented shift from beef to plant based replacement diets can thus improve nutrition in most metrics, with few, easily corrected exceptions. It also confers large environmental benefits. In Table 1, we report the resources a nationwide beef-to-plant shift will save, to which the following yardsticks

Table 1. Resource Savings Expected from a Nationwide Beef-to-Plants Dietary Shift

resource	mean (±std. dev.)	units
high quality cropland	91 (58, 124)	million acres
rangeland	771 (490, 1052)	million acres
GHG emissions	278 (220, 335)	million metric ton CO_2
reactive nitrogen	3.7 (2.9, 4.4)	million metric ton Nr

provide context. The saved high quality cropland acreage nearly equals the ≈91 million total national corn acreage.[7] The almost 0.8 billion acres of spared pastureland[3] represent 40% of the contiguous US land surface area, more than the combined area of the three largest states, Alaska, Texas and California. The ≈3.7 million metric tons of Nr savings constitute 33% of the total national N fertilizer use, and twice the Mississippi N delivery into the Gulf of Mexico.[22] Finally, the ≈278 million metric tons CO_{2e} averted emissions represent 4% and 47% of the U.S. total and direct agricultural (excluding uncertain emissions related to land use changes) emissions.[23] These results are consistent with previous comparisons of the environmental performance of animal and plant based diets.[24] Our analysis clearly does not address all relevant environmental impacts and thus further developing performance metrics, especially ones combining nutritional, environmental and other societal objectives, is essential for devising coherent, readily mutually comparable results and for identifying synergies and trade-offs among varied environmental objectives.[24]

Assuming no further changes to the U.S. agricultural enterprise beyond the considered replacement of beef with plant items or any rebound effect or indirect land use changes arising elsewhere as a response to this shift,[10] this dietary shift can significantly mitigate several major national environmental challenges, such as the Gulf of Mexico Dead Zone, and multifaceted damage to semiarid western lands.[25] By ceding such vast relatively wild rangelands, the shift will also help restore populations of such key species as wolf or bison, among many less charismatic ones, that have been on the losing side of competition with ranching for over a century.[26] Further east, the spared 92 million crop acres will be able to support much additional production of fruit, vegetables, grain or legumes for direct human consumption. To quantify this, consider the examples of wheat and apples, whose 2014 full national acreages were 46 and 0.3 million acres,[7] with only ≈16 million acres devoted to wheat for direct human consumption. If fully reallocated to such wheat and apples while maintaining the current caloric ratio of the two, the 92 million high quality cropland acres that the considered dietary shift stands to spare can thus support a 600% increase in wheat plus apple caloric availability. Alternatively (assuming no biofuel expansion), this Midwestern land can rewild,[27] restoring currently strongly altered landscapes, and providing wildland spatial contiguity that is essential for biodiversity maintenance and wildlife adaptation to such anthropogenic perturbations as changing climate or human occupation.

Some readers, even among those persuaded by the calculations themselves, may find the deployment prospects of the explored shift limited. While we are in no position to refute this view, the rise of approximate annual per capita beef consumption from 20 to 40 kg over 1930−1980 and subsequent decline to 25 kg in 2012[6] suggests that U.S. beef consumption strongly responds to economic, demographic or cultural stimuli, and is more elastic than the above sentiment suggests. Yet further research into social and economic ramifications of such a dietary shift, and consumer responses to it, is clearly necessary for its successful deployment.[28]

Protein, mass and energy conserving plant-based replacements to beef in the U.S. diet are thus readily achievable, and can significantly reduce resource use and improve diet related health outcomes.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01006.

Additional information as noted in the text (PDF)

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Notes

The authors declare no competing financial interest.

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