A model for 'sustainable' US beef production

(article begins on next page)

Possible Scope of "Sustainable" U.S. Beef

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Food production dominates land, water and fertilizer use, and is a greenhouse gas source. In the U.S., beef production is the main agricultural resource user overall, and per kcal or g protein. Here we offer a possible, non-unique, definition of "sustainable" beef as that subsisting exclusively on grass and byproducts, and quantify its expected U.S. production as a function of pastureland use. Assuming today's pastureland characteristics, all pastureland U.S. beef currently use can "sustainably" deliver ≈45% of current production. Rewilding this pastureland's less productive half, ≈135 million ha, can still deliver ≈43% of current beef production. In all "sustainable" scenarios the ≈32 million ha of high quality cropland beef currently use are reallocated for plant based food production. These plant items deliver 2- to 20-fold more calories and protein than the replaced beef and increase delivery of protective nutrients, but deliver no B_{12}. Increased deployment of rapid rotational grazing or grassland multi-purposing may increase sustainable beef production capacity.

The resource intensity per unit protein mass of beef as currently produced is 10-50 times higher than that of most animal and plant based food alternatives[1–5]. Thus, diet-related environmental burdens_which include using 47% of the national land surface area[6], application of $\geq$70% of the full national reactive nitrogen (Nr) burden (table 5 of ref. 7), 40% of consumptive freshwater withdrawals[8], and production of 20% of the national greenhouse gas (GHG) emissions[9]_can be reduced by improving beef production efficiency or replacing beef by other protein sources[1]. Leaving exploration of improved beef production efficiency to future contributions, here we focus on partial replacement of beef as currently practiced by alternative protein sources, a change likely to also improve health[10–12]. However, the above estimates of beef's resource intensity reflect the modern (see SI) U.S. beef industry, which relies not only on rangelands (pasture and locally produced hay) but also on grains, hay and silage grown on prime croplands where most environmental costs are incurred[3] . The environmental burdens of current beef could thus potentially decrease significantly if beef were derived solely from byproducts and grasslands, resources unsuitable for alternative forms of food production. Ideally, such beef production changes would be accompanied by enhanced grassland productivity (e.g., direct integration of cattle ranching with agriculture, enhanced rotations[6–8], increased reliance on legume enriched paddocks[13]), and embedded in broader structural changes that take nimble advantage of resource multi-purposing[9] (e.g., high-yield silvopastoral systems in which beef and timber share the same land[14]). Here, however, we set out to explore the narrower problem of quantifying "sustainable" beef availability under existing conditions and practices[15]. We also deliberately avoid the debate between the competing views of pastured beef as either the source of beef's environmental and nutritional liabilities[16–18] or as the key to reversing them[19–21] while improving nutrition[22]. Instead, we pose the following questions. Assuming our non-unique, surely contestable definition of "sustainable" beef (see the Methods section), how much of it can be produced in the U.S.? Beyond quantity, if the U.S shifted to "sustainable" beef, what would be some key nutritional and environmental implications for the average American?

Results

The amount of sustainable beef the U.S. can produce is plotted as a function of the utilization level of current pasture lands in Fig. 1 (quantified in mass units, left axis, or as percentage of today's beef availability of 460 g person^{-1} week^{-1}, right axis). Despite the recent doubling of distillers' grains utilization, byproducts provide ≈10% of today's beef feed consumption. Byproducts alone could therefore support a rather small sustainable beef industry, even when disregarding minimum dietary roughage required for healthy cattle nutrition. With the added utilization of all current beef pastureland ($f = 1$), the weekly per capita beef availability increases to 205 g, or 45% of today's per capita beef consumption. Cutting this pastureland use in half (reducing pastureland occupation to ≈135 million ha, corresponding to $f = 0.5$) by abandoning less productive grasslands reduces beef availability only slightly, to 200 g or 43% of present values. This 2 percentage point difference in beef availability may arguably be too small to outweigh the environmental benefits of leaving this unproductive marginal pastureland for wilderness conservation.

Importantly, any of the sustainable beef scenarios considered above would free up the ≈32 million ha of high quality cropland the beef industry currently uses for crop based feed[4], as well as all the reactive nitrogen and irrigation water annually applied to them, 3.1 billion kg and 27 billion m^3 respectively[4]. This use of natural resources represents 21%, 28% and 24% of the national total agricultural uses of these resources. It would also avert the GHG emissions associated with the current use of these high quality croplands[4], about a third[18] of conventional beef's current total ≈267 billion kg CO_{2eq} y^{-1}. These resources could be reallocated to production of more efficient alternative food items (foods that require less environmental resource per unit protein), or conserved, negating further environmental degradation.

Of the four considered limiting resources, land is unique in that it is finite, unlike the other three, whose availability can be technologically augmented. In Fig. 2 we thus quantitatively explore the consequences of reallocating the ≈32 million high quality cropland hectares (currently used to produce the crop-based portion of U.S. beef cattle feed) to the production of several plant food alternatives (see SI). We assume that all these considered alternatives receive their current mean resource inputs per ha, as consistent with their current mean yields. Reallocating land currently used for production of feed for beef to the production of feed for pork, e.g., will yield about 4 times as much pork calories as the lost beef calories or an approximate 3-fold net gain (Fig. 2a, right axis), and just under 3 times the protein or an approximate net protein doubling (Fig. 2b, right axis). The figure shows that land reallocations to any of the considered alternatives would enhance delivery of human-edible calories now provided by beef 2- to 16-fold (Fig. 2a) while increasing protein delivery 2- to 24-fold (Fig. 2b). The considered land reallocations thus offer large caloric and protein gains per high quality cropland hectare while reducing agricultural resource uses.

In Fig. 3, we perform a nutritional analysis of the reallocation of the high quality cropland beef currently used to other plant and animal based alternatives by comparing the macro- and micronutrient delivery by beef and the alternatives. The figure shows that principally due to the very low feed-to-food protein conversion efficiency of beef[23], its low protein yield—37 kg $(\text{ha} \times \text{y})^{-1}$ as compared to soybeans' 914 or peanuts' 667 kg $(\text{ha} \times \text{y})^{-1}$—results in land reallocations maintaining or expanding delivery of protein, energy and carbohydrates (but differing amino acid compositions may limit the kg-for-kg interchangeability of beef and some alternatives). Reallocating land to 8 of the 14 plant-based alternative items add to protein and energy delivery half or more of the current full per capita dietary delivery (see the SI for a definition of the latter). At almost 2 kg protein per week, the added per capita protein delivery by the most protein dense alternative, soybean (or its derivative tofu), is enough to meet in full the dietary protein needs of four additional people. This means that every individual who commits to halving their beef consumption and reallocating the freed cropland to soybeans can not only fully recoup the lost nutrition due to reduced beef availability, but also meet the full protein needs of four additional people. While adding carbohydrates and sugar intake may raise concerns, the added carbohydrates are almost exclusively complex and of the low glycemic load, slowly digested variety, and the sugar addition is trivial compared to the ≈400 kcal d^{-1} of added sugar[24] the mean U.S. adult uses, allaying this concern. All plant alternatives provide more protective total and soluble fiber intake than beef's zero. Similarly, the intake of most vitamins and minerals is maintained or enhanced under the reallocation. Vitamin B_{12} is a well-known exception, which only the reallocation to poultry and dairy increase modestly. This observation is the basis for the important and firmly established[25] necessity for B_{12} supplementation of pure plant based diets.

Changes in the amount of unsaturated fatty acids (FA in Fig. 3) are mixed and mostly modest except for soy, tofu and pork, which increase the intake of these beneficial fatty acids appreciably. For soy products and the animal alternatives, these positive dietary changes may be potentially offset by additions of saturated fat, with the animal alternatives also adding cholesterol. Overall addition of protective phytomicronutrients intake is highly varied, with significant gains limited to soy, peas, sweet potatoes and snap beans. Lastly, while sodium intake increases, undesirably, under the reallocation, even the highest additions associated with reallocation to sweet potatoes are ≤100 mg, about 4% of the recommended daily intake of 2300 mg, and thus trivial compared to delivery by added salt. Focusing on all plant and poultry alternatives, and on all nutrients, we conclude that the land reallocations we consider here would be nutritionally safe and mostly beneficial. This conclusion joins a voluminous literature documenting the health benefits of primarily plant based diets[10,12,26–29].

Finally, we quantify the environmental consequences of full cropland reallocation from beef feed to the alternatives considered above. For the three key environmental metrics impacted by agriculture (water usage, GHG emissions, and fertilizer burdens[1,3,4,30]), Fig. 4 shows the resources saved by the reallocations (resource use by the replaced beef minus the resource use by the plant alternatives) as percent of the total resource use by current beef production. A value of 40%, e.g., means that after the land reallocation, the alternative crop uses 60% of the current resource use by the usurped conventional beef. The mean resource savings by all alternatives are 40-80% of the use by conventional beef, thus offering very significant potential improvements. Note that while enhanced methane production by pastured (as distinguished from mostly grain fed[18]) beef results in a 20-30% higher CO_{2eq} burden[21], all the plant alternatives offer net GHG savings.

Discussion

If Americans reduced their mean beef consumption from the current ≈460 g $person^{-1}$ $week^{-1}$ to ≈200 g $person^{-1}$ $week^{-1}$ (corresponding to $f = 0.5$), the U.S. beef industry could become environmentally sustainable by the narrow definition of this paper. Note however, that we intentionally leave open for future work the questions of whether this is the best definition, whether this outcome is environmentally optimal, or how much of the shortfall can be made up for by grazing improvements. In this $f = 0.5$ scenario, beef would be raised on existing rangelands, claiming about half of the land it currently uses, supplemented by agricultural byproducts. This will allow repurposing high quality croplands now being used to grow feed for industrial beef operations for other, more environmentally benign and nutritious food types. Our results complement numerous earlier nutritional[10,12,26–29,31] and environmental[20,32] analyses, and suggest that given equal beef supply and demand, small modifications in people's dietary habits, moving toward more plant-based diets, or even just choosing chicken or pork over beef, would dramatically enhance the environmental sustainability of the agricultural industry in the U.S.

Methods

To quantify the amount of "sustainable" beef that can be grown in the U.S., we consider alternative "sustainable" beef production scenarios that rely exclusively on rangeland products (pasture and small amounts of locally baled hay) and agro-industrial byproducts[33] (such as citrus peel, distillers grains or millfeed) that are utilized as beef feed.

The "sustainable" scenarios differ only in their rangeland contributions (pasture plus locally baled hay) to overall availability of beef feed, which depend on f, the fraction of the ≈275 million ha of pastureland the U.S. beef industry currently uses[3,4] (see SI for details). A given f splits this total into the utilized and unutilized parts, where we chose the most and least productive areas to correspond to f and 1-f respectively, with the mean productivity of the utilized area declining with rising f. A given "sustainable" scenario is thus characterized by a unique total beef feed energy availability, $e_T(f) = e_B + e_P(f)$, where e_T *is the total feed* energy available for beef in the considered scenario, e_B is the invariant feed energy contributed to beef rations by byproducts (fixed at today's levels), and e_p is the f dependent pasture contribution to total available feed energy.

Estimating how much beef can be raised sustainably (as defined above) on existing pastureland requires estimating $e_p(f)$ *or* forage production, which increases with rising pasture land area and/or forage yield and digestibility. Estimating forage energy utilized requires estimating the yield distribution throughout the widely variable pasturelands used. Yet no official geographically explicit and comprehensive estimate of geographical variability of beef pasture consumption per unit area exists. Estimates of overall mean U.S. metabolized pasture yield (taking indirect note of raw yield, grazing utilization fraction, and digestibility) are[3,4,34] 430-520 kg dry matter (DM) $(\text{ha} \times \text{y})^{-1}$. Given the size and diversity of U.S. pasturelands—occupying over four times the area of France and spanning such extremes as the moist, lush southeast[35] and the arid southwest—even if the actual mean U.S. metabolized pasture yield indeed falls within this quite narrow range, it sheds no light on the wide range of metabolized yields expected of such varied grasslands. The utilized pasture yield function (shown in the inset of figure 1) is constrained to reproduce the current mean value, with details in the SI. Carefully derived based on transparently documented logic, and likely a reasonable quantitative proxy, the function is nonetheless somewhat uncertain (see SI). Consequently, our results for $f < 1$ must be considered an intriguing and novel early estimate, not the definitive final word on what "sustainable beef" is or the amounts of it the U.S. can produce under deliberate partial relinquishing of the pastureland beef currently use. Regarding full usage of pasture land (corresponding to $f = 1$), the shape of the function is irrelevant and the results are independent of it qualitatively or quantitatively.

Apart from pasture, feed in our sustainable beef model also includes agro-industrial byproducts, the refuse of processing grain, sugar beets or fruit into packaged foods. Absent further use, this abundant, nutrient-dense organic matter, ideal for livestock feed, would require substantial effort, energy and environmental costs to dispose of properly. Yet because they are relatively affordable, byproducts enjoy robust demand as feed. Updating our earlier work[3,4], we assume the amount of byproducts fed to cattle in the sustainable scenarios is the 2010-2015 mean, just under 10% of all beef feed energy[3,4,23]. This contribution is more than double that in our earlier work, reflecting the rapid rise in utilization of distiller grains (a byproduct of the ethanol industry) as feed in the early 21st century (see SI for further discussion). In summary, striving for the most up-to-date estimate of “sustainable” beef availability, here we use 2015 data for byproducts while still using 2000-2010 means for other (largely unchanged) feed sources. Because byproducts still contribute about 10% of total beef feed, this inconsistency impacts the results negligibly.

Data availability

All data generated or analyzed during this study are included in this published article and its Supplementary Information files.

Code availability

The main Matlab code on which this study is based is included as a Supplementary Information file.

Contributions

G.E., A.S., R.M., S.G., D.G. and M.R. initiated the study. G.E. compiled the data, conducted all analyses, produced the graphics, and wrote the manuscript. R.M. edited an initial draft. All authors edited and commented on subsequent drafts, and discussed the results.

Competing Interests

None of the authors has any competing or conflicting interests.

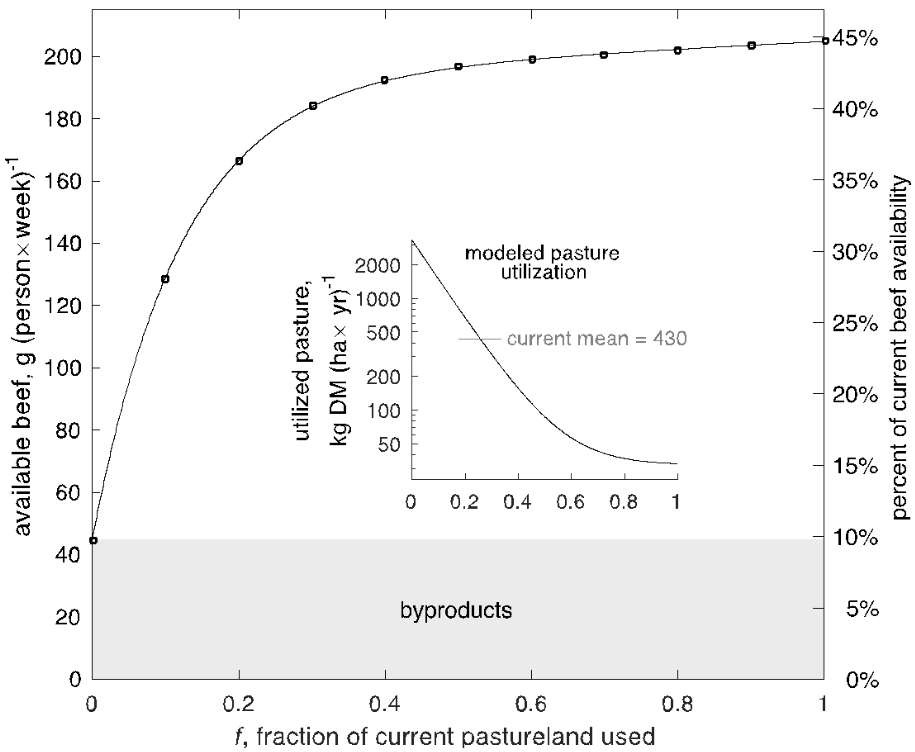

Figure 1: Per capita weekly availability of "sustainable" beef as a function of the utilized fraction *f* of current beef pastureland (approximately 0.3 billion hectares). At any *f* value along the horizontal axis, overall feed available for beef is the sum of the small fixed contribution of byproducts (bottom grey rectangle, derived in the text and the SI) and the *f*-dependent pasture contribution. This overall metabolizable feed available for beef is recast as beef availability (left axis) using beef's energy conversion, ≈0.03 available beef kcal per ME feed kcal[3,4,23]. At any *f* value, the pasture-based feed energy contribution (the integral of the yield function from 0 to *f*) is added to the above fixed byproduct contribution to form the overall feed energy the sustainable beef can supply at that *f* value. Beef availability is also shown (right axis) as percent of today's beef supply (≈460 g person^{-1} week^{-1}) that the sustainable feed can produce. Open squares highlight 0. 1 *f* increments. The inset shows the assumed utilized yield function in metabolizable kg dry matter (DM) pasture per ha per year, also as a function of the fraction *f* of current pastureland used. See SI for further details. Because no data providing a direct estimate of today's national mean pasture mass yield exist, we show here our indirectly-derived estimate of ≈ 430 utilized kg DM[3,4] ha^{-1} y^{-1}(horizontal gray line). The equivalent pasture yield shown in the inset is the assumed ME yield divided by representative mean forage energy density[3,4], 2140 kcal ME (kg DM)$^{-1}$, as described in details in the SI. It is *not* an estimate of the overall grass aboveground productivity, but only of its utilized—eaten and metabolized—fraction.

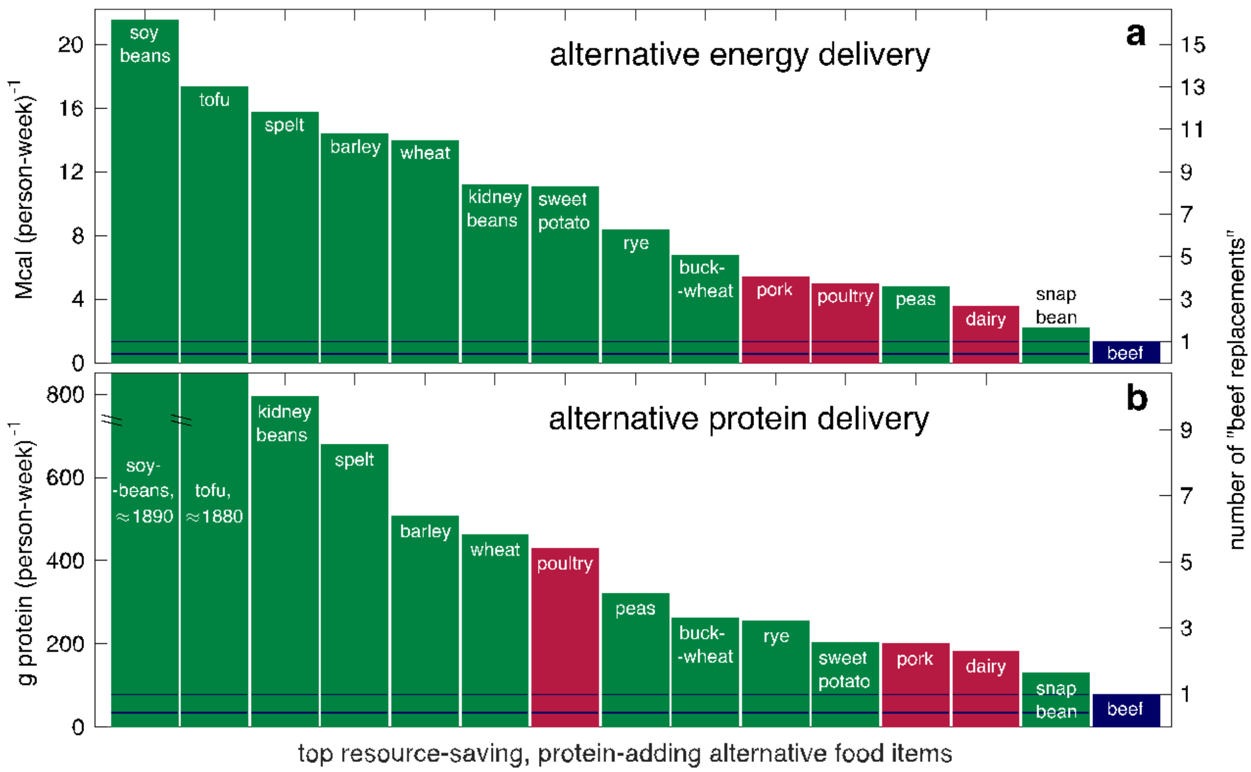

Figure 2: The alternative per capita food energy (**a**) and protein (**b**) delivery associated with reallocating the ≈32 million high quality ha currently used to produce crop based feed for U.S. beef cattle to the shown alternatives. See SI for specific calculation details. Plant and animal alternatives are shown in green and red respectively. The top blue horizontal lines show the amounts that beef currently delivers. The (nearly overlapping) middle and bottom blue lines show sustainable beef availability when using all ($f = 1$) or half ($f = 0.5$) of the pastureland currently allocated for beef.

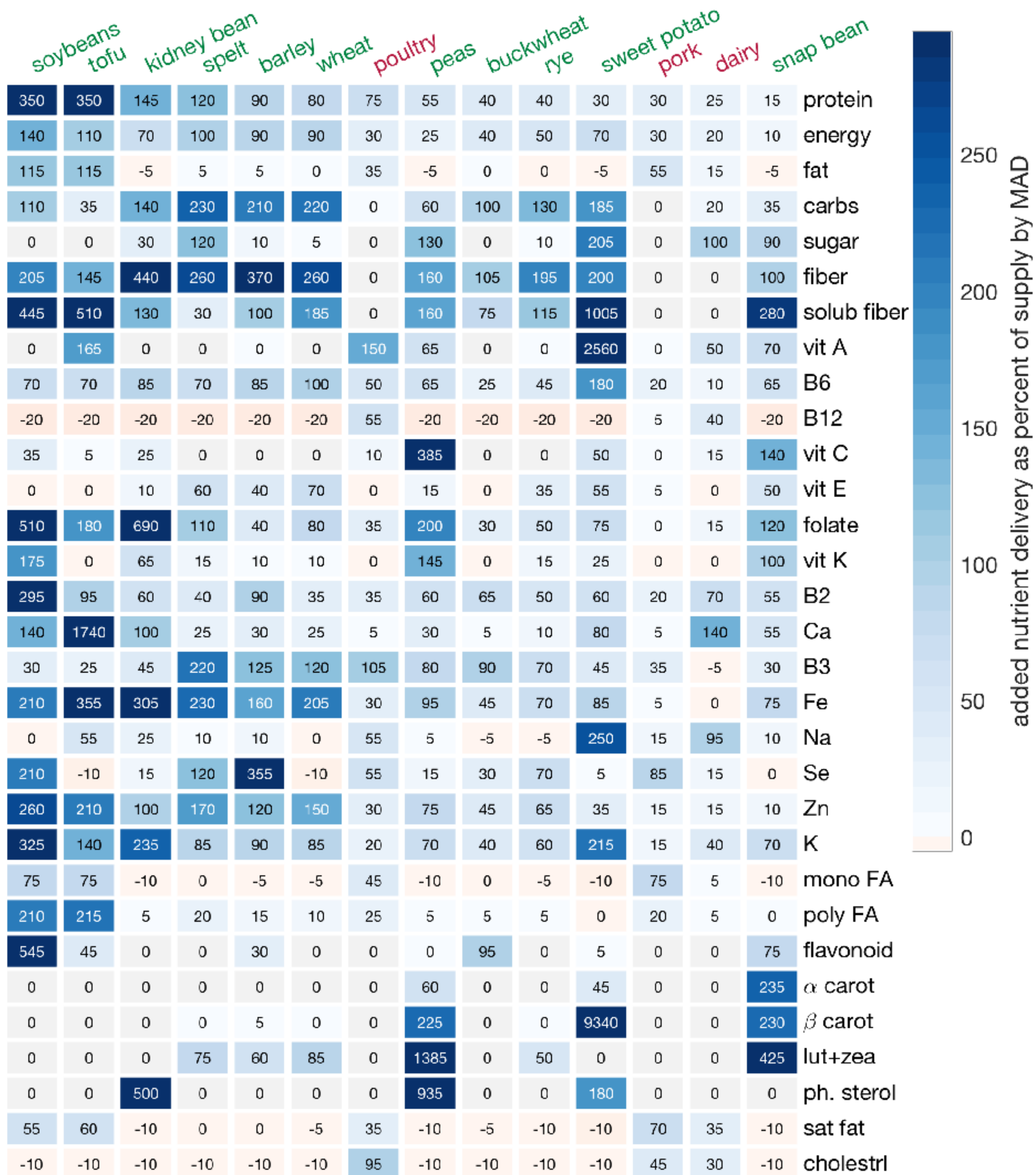

Figure 3: The nutritional consequences of producing sustainable beef (that uses only industrial byproducts and the full pastureland currently used by beef, i.e., at $f = 1$) and the associated reallocation of cropland (currently used for producing feed for beef) to each of the shown alternatives (in green or red for plant or animal based items). Each colored cell shows the amount of a nutrient delivered by the alternative food item minus the net loss due to reduced beef production (the loss of the full conventional beef amount minus the smaller gain due to permitted “sustainable” beef), expressed as a percent of the delivery of the same nutrient by the truncated MAD (with details in the SI). For instance, cell (1,1) shows that if the cropland currently used for beef feed

production is fully reallocated to soybeans, the added soy protein minus the net loss of beef protein would amount to a 350% increase in the protein content of the mean American diet.

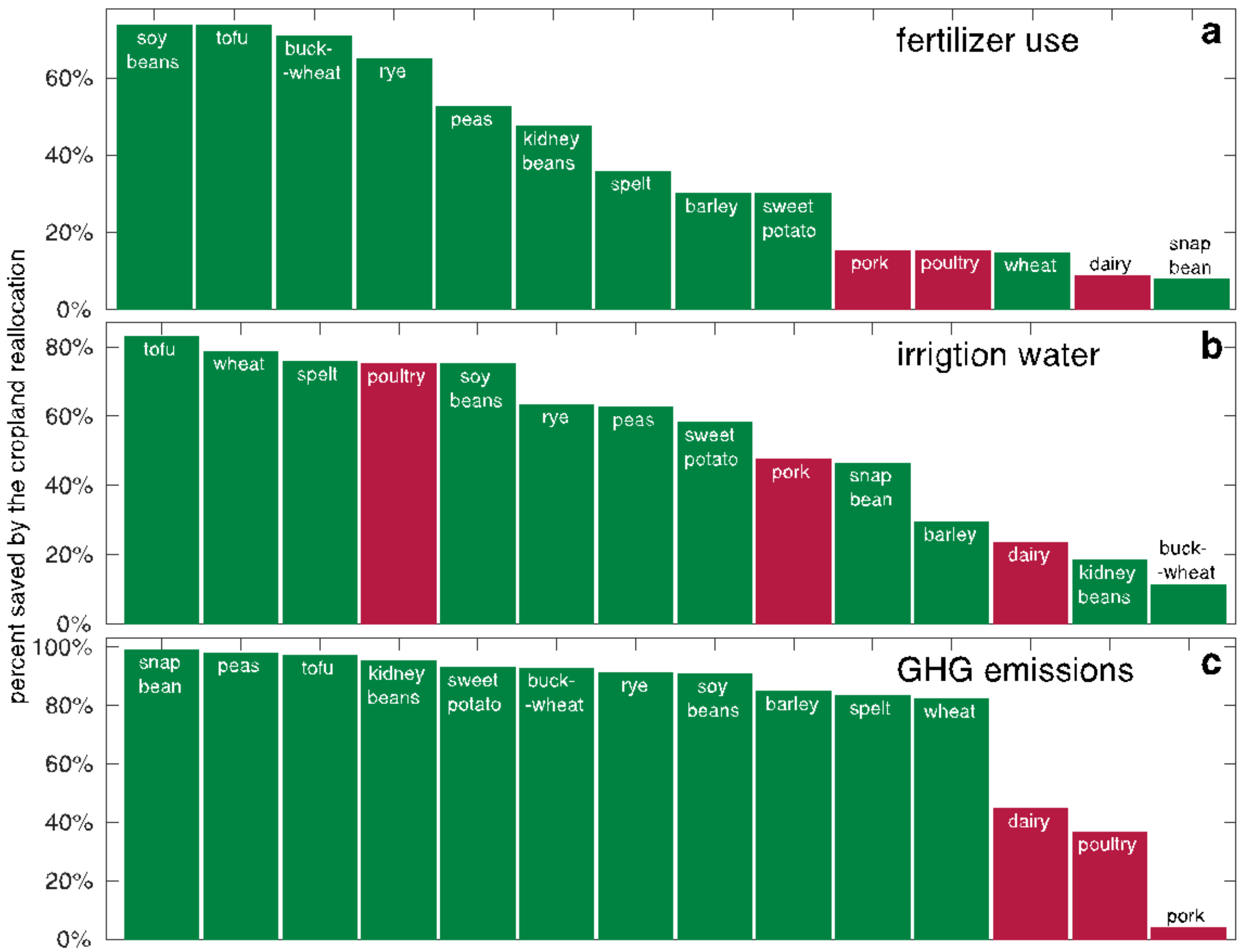

Figure 4: Resource savings associated with the beef cropland reallocation to the shown plant (green) and animal (red) based alternatives. These savings are the resource use by the replaced beef minus the resource use by the alternatives using the full reallocated croplands. To allow comparisons across resources (the three panels), we express these savings as percentage of the amount currently used for production of beef feed on the reallocated cropland. This means, e.g., that the tenfold increase in protein delivery afforded by reallocation of beef cropland to kidney beans (Fig. **2b**) also saves half of all the fertilizer beef feed currently uses on the reallocated cropland (**a**), as well as 20% of the irrigation water (**b**) and 90% of the GHG emissions (**c**).

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