Geophysics and nutritional science: Toward a novel, unified, paradigm

Gidon Eshel[1] and Pamela A. Martin[2]

[1]corresponding author; Division of Science, Mathematics and Computing,

Bard College, 84 Alford Road, Great Barrington, MA 01230

Email: geshel@gmail.com, Tel: (413) 528-7299

[2]Department of the Geophysical Sciences, The University of Chicago,

5734 S. Ellis Avenue, Chicago, IL 60637

Email: pmartin@uchicago.edu, Tel: (773) 834-5245

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Abstract

We present a few basic geophysical processes which collectively indicate that several nutritionally adverse elements of current western diets also yield environmentally harmful food consumption patterns. We address oceanic dead zones—at the confluence of oceanography, aquatic chemistry and agronomy—which is a clear environmental problem, and agriculture's effects on the surface heat budget, because of its exemplifying the unknown, complex and sometimes unexpected large-scale environmental effects of agriculture. We thus delineate the significant alignment in purpose of nutritional and environmental sciences. We identify red meat, and to a lesser extent the broader animal-based portion of the diet, as having the most environmental impact, with clear nutritional parallels.

1 Introduction

In recent years, recognition of the substantial and inexorably expanding deleterious environmental consequences of food production has been steadily widening among the scientific community and lay audiences alike (1-5). In popular accounts, these consequences and the scientific, political, social and cultural issues they raise have benefited from widely diverse, multi disciplinary and integrative treatment (4,6). Conversely, in keeping with the mission, tradition, and culture of science, scientific accounts of the same topics, in particular novel, original, scientific publications, have been largely narrowly focused and distinctly disciplinary. Yet intellectually and academically, the tensions and interactions between food production and the physical environment are multi-faceted, carving a niche at the confluence of numerous fields of inquiry. As such, the successful treatment of food–environment interactions requires a dialog across traditional disciplinary boundaries. While initiating and sustaining such a dialog is notoriously challenging, it is also potentially highly influential, because of the multitude of backgrounds, skills, talents and styles a successful trans disciplinary collaboration will bring to bear on the problem. The purpose of this paper is to further a subset of the necessary dialog, that between geophysics and nutritional sciences.

Most readers may readily identify the relevance of geophysics, as the physical aspects of food production fall into the traditional provinces of such branches of geophysics as meteorology, oceanography, climate science, hydrology and soil science, among others. What some readers may find less obvious is why nutritional science may wish to concern itself with the environmental consequences of food production. The reason is that nutritional science plays a central role in shaping food–environment interactions, and is a key to replacing the current, environmentally (7) and nutritionally (8) injurious, food production system with a sustainable one. By affecting dietary choices of individuals and the public (9-10), and thus national and global food consumption patterns, dietary recommendations have significant, far reaching, geophysical corollaries, as discussed briefly in Section 2 below. Importantly, the intensity and prevalence of many of the geophysical consequences of food production are strongly affected by dietary choices. It follows, therefore, that much of the current environmental degradation due to food production can be rectified by a more thoughtfully designed individual and national diet. Specifically, the combined effect of reasonable and achievable individual dietary modifications stands to have enormous environmental benefits. Enhancing the likelihood of such diet-mediated environmental improvements is this paper's broader objective.

2 Some Geophysical Consequences of Food Production

In this Section we describe some nutritionally relevant geophysical consequences of food production and agriculture, reserving to Section 3 the discussion of the effects dietary choices and nutritional science can have on the scope of the environmental issues described below. While the scope of food production–geophysics interactions is extremely broad, comprising, e.g., stream degradation, toxic effluent, air pollution, water consumption, below we highlight two particularly complex and multi-faceted geophysical issues, ocean "dead zones" and agricultural effects on the surface heat balance and atmospheric structure.

2.1 "Dead Zones"

"Dead zones" are vast swaths of the coastal ocean where levels of dissolved oxygen in the seawater are at times low enough to cause mass shell-fish and fish kills. Oceanographers have known for decades that many dead zones are directly attributable to fertilizer use in river basins that drain into the affected coastal oceans (11-13). The essence of the dead zone mechanism is as follows. Excessive fertilizer application, compounded with artificially enhanced water availability (see below), results in fertilizer leaching into surface and ground waters, eventually working its way into the coastal ocean. Once there, nutrients leached from unused fertilizer interact vigorously with the local environment. The main reason for this efficacy is that in summer, when sunlight is abundant, the foundation of the oceanic food web—algal primary productivity (photosynthesis)—is mostly limited by nutrient availability. Consequently, the added nutrient the leached fertilizer introduces into the ocean enhances, sometimes dramatically, algal abundance. Upon death of the (short-lived) algae, this excess organic matter decomposes in the water column and near the bottom, following a chemical reaction that, like breathing, can be reasonably described as "reversed photosynthesis". This decomposition thus consumes oxygen dissolved in the seawater, suppressing its ambient levels below those necessary for many ocean life forms, with ensuing die-offs.

There are various important contributions of agriculture to the dead zone problem. The direct effect—fertilizer application on fields in the drainage basin—is the most straightforward. In addition, agriculture accelerates the hydrological cycle. First, tilling, plowing and other soil cultivation methods enhance runoff of precipitated water from the surface (14-15). In addition, many intensively cultivated regions (such as the Midwestern United States, hereafter US) are heavily "tiled". In its various forms, "tiling" strives to improve root system aeration by underlaying agricultural land with tiles (mostly outdated now) or semi-permeable pipes that accelerate the flow of sub-surface water toward ditches and streams (16). Finally, the surface drainage system—the network of creeks, streams and rivers—of most intensive agricultural provinces is significantly altered by humans to control flows and render them more predictable, manipulable or manageable. These alterations often include the introduction of irrigation ditches, "straightening" stream meanders, and diverting surface flows through concrete fortified channels.

Intensive agriculture further contributes to dead zones by enhancing substantially local water availability in large, contiguous, agricultural regions. Perhaps counter-intuitively, enhancement by irrigation is often not quantitatively the most important. That role is reserved to local recycling of precipitation, the supply of water vapor to the air column by re-evaporation of precipitate already on the ground. Precipitation requires supply of water vapor to the lowermost atmosphere in the precipitating region. In many places, the lion's share of this supply is wind borne; when the wind transports more water vapor toward a given location than it transports away from it, water vapor abundance in the air at that location will rise with time. In some regions, another important water vapor source for future precipitation is local recycling of previously fallen precipitation. For readers familiar with the climate of the north eastern US, an example of this process is the intensely uncomfortable relative humidity peak that often follows summer afternoon rain showers, when the ground is warm enough to cause collecting precipitate to rapidly evaporate back into the lower atmosphere. Vegetation plays a similar role. Green leaves must open their stomata to take up atmospheric carbon dioxide (CO_2) required for photosynthesis. The price they pay for this is so-called evapo-transpiration, the loss of leaf water to evaporation. Agriculture, especially row crops, has a similar—but artificially amplified—effect, as in many important agricultural regions such crops replace what would have otherwise been considerably less lush vegetation. This is obviously true in the southern California Central Valley, or the south western US (e.g., around Tucson, Arizona). A less dramatic, yet volumetrically more important, example of that would be the North American Great Plains, especially between $\sim 100°$W to the east and the Rockies to the west. The result of this is that, on average, agriculture, especially row crops, tends to supply the lower atmosphere with water vapor it otherwise would not have had. The additional water vapor supply has several important effects, such as cooling the surface (17) and modifying cloudiness patterns (18).

A quantitative example of the overall change resulting from these processes is the estimate (19) that human induced evapo-transpiration (plant mediated evaporation) in the Mississippi Basin enhanced natural evaporation by 12 mm yr^{-1} during the final decades of the Twentieth Century, and that this evaporation augmentation is rising at a rate of 2.6 mm yr^{-1}—or 22%—per decade. For the same period, the same authors also report a precipitation increase rate of approximately 18 mm yr^{-1} per decade. While clearly not all of this observed precipitation rise is attributable to the ubiquity of row crops in the Mississippi Basin, some yet to be determined portion thereof is (20).

All of the above hydrological effects of agriculture reduce the average time water spends in the soil, and accelerate the land-to-ocean branch of the hydrologic cycle (17-20). The shorter residence time of liquid water in the soil means that solutes such as nutrients from unused fertilizer are subject to a briefer, less complete, processing by soil flora. The overall result is enhanced nutrient export at the expense of reduced local nutrient cycling. Such suppression of local nutrient recycling and augmentation of nutrient export by acceleration of the hydrological cycle, compounded by vastly enhanced nutrient supply, is not only a centerpiece of the dead zone mechanism, but arguably among the single most basic and elemental criteria for geophysical sustainability of food production.

2.2 Surface Reflectivity and Other Surface Exchanges

Unlike dead zones, which are clearly an environmental problem, this Section describes a subtle effect that is not an environmental problem per se. Rather, this Section highlights environmental changes caused by agriculture, constituting a large-scale planetary experiment.

The issue of global warming is by now familiar, to some degree, to most. At the core of the problem is perturbation of the earth's surface heat budget, the balance at the earth's surface between incoming (downward) and outgoing (upward) heat fluxes. In most popular and scientific accounts, the focus is the Greenhouse Effect, modification of which by human activity—primarily the emission of CO_2 accompanying fossil fuel energy consumption—is thought to be the primary vehicle of human-induced climate change. In this effect, so-called greenhouse gases (GHGs, e.g., CO_2, methane) absorb some long wave radiation emitted upward by the earth surface, and radiate the absorbed energy back down, toward the earth's surface, thereby warming the surface slightly more than otherwise. Because most GHGs interact with (absorb) long wave radiation but are neutral with respect to short wave (solar) radiation, the focus is firmly on the long wave part of the radiative budget.

Less broadly appreciated is that the variable most relevant to climate is not the surface radiative budget, but rather the surface *heat* budget, which involves long wave radiation as well as other terms such as evaporative cooling. Even within the confines of the surface radiative (rather than heat) budget, the key is not a particular contribution, but rather the overall balance, comprising both the long and short wave (incoming solar) radiation, the latter being the primary driver of earth's climate. So while perturbing the earth's long wave radiative budget by enhanced atmospheric GHG concentrations due to human activity is environmentally extremely important, the surface heat balance can be upset by other means as well. One of those means, modified surface reflectivity, is strongly linked with agriculture.

Surface reflectivity, often referred to as albedo, determines the portion of the incoming solar radiation reaching the surface that is absorbed by—and thus warms—the surface. For example, the albedo of fresh snow is approximately 0.75, which means that only 25% of the incoming solar radiation is absorbed by the surface, while 75% of it is reflected from the surface back up. Natural ecosystems agriculture replaces are typically characterized by reflectivities in the 3-12% range (21-22). By contrast, summer crop reflectivity is typically in the 13-28% range (23-24). Figure 1 shows the effect of characteristic albedo changes due to agriculture, where S_o is the incoming solar flux in W m^{-2}, and $\Delta S = S_o \left(\alpha_{\text{crop}} - \alpha_{\text{nat}}\right)$ is the change in absorbed solar flux due to cropland with albedo α_{crop} replacing a natural ecosystem with albedo α_{nat}. The perturbations of the surface radiative budget are very large. For example, at the beginning of the season, when the crop is young and its albedo correspondingly large (i.e., when a panel's right side is its relevant part), a mid-day perturbation (when the incoming solar flux can readily reach 800 W m^{-2}, panel c) is approximately 200 W m^{-2}. This is a staggering perturbation, roughly 50 times larger than the corresponding ~ 4 W m^{-2} perturbation of the surface long wave budget due to doubling atmospheric CO_2 (25). Note that the differences of Figure 1 represent only daytime (at night, with no incoming solar radiation, albedo is meaningless), and, more importantly, only areas in which cropland exists and replaces natural low albedo surfaces. In contrast, the much smaller long wave perturbation due to elevated atmospheric CO_2 and other GHGs prevails at all times, throughout the earth's surface.

Notwithstanding the above stipulations, the message of Figure 1 is extremely important. First, locally, the short wave radiative effect of agriculture can be dramatically larger than that of GHGs (17). Second, these changes can yield significant, sustained, continental scale surface temperature changes of comparable magnitude to those resulting from doubling atmospheric CO_2 (17,25). It is instructive to demonstrate the change in surface heating of a modest ΔS of, say, 70 W m^{-2},

$$\Delta\left(\delta T_{\text{soil}}\right) = \frac{\Delta \text{S}}{\rho\, c_p\, h}\, \delta t \approx 1 \text{ K}, \tag{1}$$

where K denotes degrees Kelvin. In Eq. 1, δT_{soil} denotes soil solar warming over a time span $\delta t = 4$ hours, representing, e.g., soil warming between 8AM and noon. Therefore Eq. 1 gives the change in soil warming by the sun over 4 hours due to the albedo change that yielded the solar heating change ΔS. Other terms in Eq. 1 are soil density $\rho = 10^3$ kg m^{-3} and specific heat at constant pressure $c_p = 10^3$ J kg^{-1} K^{-1}, and the thickness $h = 3$ m of the thermally active soil layer. A heating rate difference of 1 K (4 hours)$^{-1}$ is very significant for various atmospheric processes. Subjectively, we single out for a brief discussion one of those, deepening of the atmospheric boundary layer following wind generation by thermal gradients and turbulence generation by those winds.

The first thing to note is that thermal gradients set air in motion. Imagine two adjacent land parcels, one covered with forest, the other with young corn. Assuming their soil temperatures are the same at 8 AM, according to Eq. 1, by noon the corn field will be 1 K cooler. This thermal difference will accelerate air, creating wind. If the two plots are close enough to each other, the winds between them will quickly become vigorous.

Next, let us introduce the boundary layer, the lowermost, and arguably environmentally most important, part of the atmosphere (26). Air-borne pollutants and evaporated surface water, among other trace constituents with surface origin, initially collect in the boundary layer, from which they are redistributed higher in the atmosphere above by mostly sluggish vertical exchange processes. The depth of the boundary layer—its vertical extent from the surface to its ceiling—is determined by various processes, among them the rate of turbulence generation by boundary layer winds. Avoiding technicalities, it is intuitive that the more vigorous the flow, the more turbulent the fluid will be (think of the stately flow of the Hudson near New York City, as compared to a swift mountain brook, the latter being more turbulent). The same is true for the atmosphere, also a fluid. All else being equal, the more turbulent the boundary layer, the deeper it gets, and thus the larger the atmospheric container in which various trace constituents with surface origin collect. Boundary layer depth is of prime importance to relative humidity, and thus to evaporation, cloudiness and other water related atmospheric properties (17-20). As a consequence, e.g., holding all other factors constant, a deeper boundary layer will result in lower relative humidity and elevated evaporation from agricultural and non-agricultural surfaces alike. In general, all else being constant, a given water vapor source will saturate the boundary layer with respect to water vapor, and thus stop evaporation, twice as fast if the boundary layer depth is halved. Boundary layer depth is also extremely important because of its interactions with concentrations of ground-level ozone pollution, a known agricultural yield suppressor (27), and because of its prime effect on vertical distribution of water vapor, with unknown greenhouse consequences.

This Section can be summarized as follows. Embedding agricultural land within natural landscapes changes the surface reflectivity to incoming solar radiation, which results in spatially variable ground heating rates. The resultant thermal gradients yield low-level winds, which enhance turbulence in, and thus deepen, the boundary layer. Boundary layer depth affects rates of humidification by surface evaporation, rates of pollution build-up, and, more broadly, the response time of the boundary layer to any forcing. All of these processes are both strongly affected by, as well as affecting, agriculture.

2.3 Energy Consumption and Greenhouse Gas Emissions

Many of the processes involved in food production result in GHG emissions. This is important because the small amplification of the natural greenhouse effect by humans is caused by raising atmospheric concentrations of GHGs.

Agriculture and food production use fossil fuel energy, which results in emissions of mostly CO_2, as well as small amounts of other GHGs. Quantitative estimates of energy use in food production vary widely. In the US, the total is probably in the range of 10-17% of the total (28-29). Assuming a conservative 10% and taking the total US CO_2 emissions from fossil fuel combustion to be 5,639.4 Tg (terragram, a million metric tons) per year in 2006 (ref.

30, Table ES-2), energy use in agriculture amounts to emissions of

$$e_{CO_2} = \frac{5,639.4 \cdot 10^6 \text{ ton } CO_2 \times 0.1}{299 \cdot 10^6 \text{ Americans}} \approx 1.89 \, \frac{\text{ton } CO_2}{\text{person} \times \text{yr}} \tag{2}$$

where the rounded upward US population in 2006 is taken from the US Census Bureau (31, Table T1). Note that the effects of the minor omissions and simplifications of this estimate all have the same sign, rendering the above estimate a lower bound[1].

In addition, agriculture, especially animal farming, results in significant emissions of two powerful non-CO_2 GHGs, methane and nitrous oxide. Each of these gases has a different radiative effect, from each other and from CO_2. To facilitate addition of their radiative effects on earth's surface temperatures, emissions of non-CO_2 GHGs are expressed as CO_2-eq (where "eq" stands for "equivalent"), the mass of CO_2 that would have yielded the same long wave radiative forcing as the actual amounts of methane or nitrous oxide emitted, given the molecules' distinct physical structures. Together, combined agricultural 2006 emissions of methane and nitrous oxide were 618.9 Tg CO_2-eq (ref. 30, Table 6-1), or

$$e_{\text{non } CO_2} = \frac{618.9 \cdot 10^6 \text{ ton } CO_2 - \text{eq}}{299 \cdot 10^6 \text{ Americans}} \approx 2.07 \, \frac{\text{ton } CO_2 - \text{eq}}{\text{person} \times \text{yr}}. \tag{3}$$

A conservative lower bound estimate of total food production related greenhouse gas emissions is therefore

$$e_{\text{total}} \leq e_{CO_2} + e_{\text{non } CO_2} = 3.96 \, \frac{\text{ton } CO_2 - \text{eq}}{\text{person} \times \text{yr}}. \tag{4}$$

[1]one challenge to this statement may be that summing the direct ("on farm") and ammonia fertilizer production energy uses yields only about 1% of the total US greenhouse gas emissions due to energy use. We chose the above value of 10%, which we view as a lower bound, because estimates based on full life cycle analyses (28-29) are far more complete than the simple addition described above

This should be compared with the 2006 US total per capita net greenhouse gas emissions (ref. 30, Table ES-2),

$$E_{\rm all} = \frac{6318.9 \cdot 10^6 \text{ ton } \mathrm{CO_2} - \text{eq}}{299 \cdot 10^6 \text{ Americans}} \approx 21.13 \, \frac{\text{ton } \mathrm{CO_2} - \text{eq}}{\text{person} \times \text{yr}}. \tag{5}$$

of which food production is about 19%.

3 Some Effects of Nutritional Science on the Geophysical Consequences of Agriculture

In this Section, we strive to make the nutritional science community better aware of the significant alignment between desirable diet modifications guided by nutrition, and those guided by geophysics. Put differently, we wish to emphasize that what is good for an individual's health can be also geophysically and environmentally beneficial and desirable.

The single most important example of the above alignment is red meat consumption. The health costs of red meat consumption are well known and well established (32-35), and the readership of this Journal needs no reminder of this from geophysicists. As a result, the government-independent nutritional community has been progressively more emphatic in recommending reducing red meat consumption (32,36). Similar conclusions can be reached based on geophysical considerations, principally GHG emissions.

3.1 Red Meat and Greenhouse Gas Emissions

Averaged over 2000-05, the average American ingested 244.5 red meat kcals day^{-1} (37). Given the substantial losses of meat along the distribution chain, this ingested amount consumed amounts to

$$244.5 \, \frac{\text{red meat kcal}}{\text{person} \times \text{day}} \, 365.4 \frac{\text{day}}{\text{yr}} \, \frac{161.7 \text{ lb}}{104.3 \text{ lb}} \approx 138,507.44 \, \frac{\text{red meat kcal}}{\text{person} \times \text{yr}}, \tag{6}$$

where 161.7 lbs and 104.3 lbs are, respectively, the gross (carcass), and net (consumer) per capita annual meat consumptions (37). The ratio of gross to net consumption is best thought of as the consumption amplification factor due to losses during distribution to consumers of meat that has already incurred the full environmental costs of production.

The production of this amount of meat incurs both CO_2 and non-CO_2 greenhouse gas emissions, the former being mostly due to fossil fuel energy consumption, the latter mostly from anaerobic organic matter decomposition associated with ruminant digestion, and manure management. To quantify CO_2 emissions due to fossil fuel energy consumption, we use the calorically-weighted mean energetic efficiency of red meat in the mean American diet, 9.3% (ref. 38, Table 3; the value means that a variety of fossil fuels containing a total of 100 calories is consumed during the course of producing 9.3 edible red meat calories). The national mean red meat consumption therefore entails consumption of $138,507.44/0.093 = 1,489,327.4$ fossil fuel kcals $\text{person}^{-1}\ \text{yr}^{-1}$. To convert these amounts to CO_2 emissions, we use a conversion factor derived from the total US economy emissions and energy consumption (37), 0.2778 gr CO_2 (fossil fuel kcal)$^{-1}$. Using this conversion factor, fossil fuel energy use required to sustain the national red meat consumption amounts to the emissions of

$$1,489,327.4 \frac{\text{fossil fuel kcals}}{\text{person yr}} \times 0.2778 \frac{\text{gr CO}_2}{\text{fossil fuel kcal}} \times \frac{1}{10^3} \frac{\text{gr}}{\text{kg}} \approx 413.73 \frac{\text{kg CO}_2}{\text{person yr}}. \tag{7}$$

We now turn our attention to emissions of non-CO_2 GHGs associated with the red meat portion of the mean American diet. For each meat type in the red meat mixture, we use a non-CO_2 emission factor, the mass of CO_2 that would have caused the same radiative forcing as the actual amounts of methane and nitrous oxides emitted in the course of producing every kcal of meat. The non-CO_2 emission factors we use for beef, pork and lamb are, respectively, 9.48, 1.52 and 2.82 gr CO_2-eq (meat kcal)$^{-1}$ (ref. 38, Table 5). Deviating from our earlier work to reflect more recent national meat consumption statistics, here we take the national red meat mixture to comprise 57% beef, 42% pork and 1% lamb (37). The weighted average non-CO_2 emission factor appropriate for the red meat portion of the national diet is therefore $9.48 \times 0.57 + 1.52 \times 0.42 + 2.82 \times 0.01 = 6.07$ gr CO_2-eq (meat kcal)$^{-1}$. The emissions of non-CO_2 GHGs associated with production of the red meat portion of the national diet is therefore

$$138,507.44 \ \frac{\text{red meat kcal}}{\text{person} \times \text{yr}} \ 6.07 \ \frac{\text{gr CO}_2 - \text{eq}}{\text{red meat kcal}} = 840.74 \ \frac{\text{kg CO}_2 - \text{eq}}{\text{person} \times \text{yr}}. \tag{8}$$

In summary, the total (energy-related CO_2 plus non-CO_2) GHG emissions associated with producing the red meat portion of the national diet is therefore $413.73 + 840.74 = 1,254.47$ kg CO_2-eq person^{-1} yr^{-1}.

Referring to calculations presented earlier in this paper, this annual per capita emission amounts to $100 \times 1.25447/3.96 \approx 32\%$ of the per capita dietary GHG footprint, and $100 \times$

$1.25447/21.13 \approx 6\%$ of the per capita overall GHG footprint. With a 2000-05 mean US net ingested caloric input of 2,704 kcal person^{-1} day^{-1} (37), the red meat portion, 244.5 kcal person^{-1} day^{-1} (37), is calorically only 9%, yet it results in 32% of the total GHG emissions.

3.2 The Need for Land

The intensity of the effects discussed in Section 2 is proportional to the surface area dominated by agriculture; the more land is used for growing food, the stronger and more ubiquitous these effects are. There are several important ways by which dietary choices, and thus nutritional science, affect the demand for land. We briefly discuss below the key issue, growing grain for animal feed.

Of the surface area of the contiguous 48 states excluding Alaska and Hawaii, about 1,026 million acres, or over 54% of the total, was devoted to agriculture in 2002 (39). Crops alone occupied 442 million acres, $\sim 23\%$ (39). Averaged over 2000-06, corn, sorghum, barley and oats consumed 79.1, 8.4, 4.7 and 4.4 million acres each (40). Over this period, the respective portions of those crop yields used for animal feed was 57%, 42%, 33% and nearly 100%. In addition, hay production averaged over the same period 62.3 million acres, and wheat—of which $\sim 22\%$ is used for feed (41)—occupied ~ 60 million acres. Thus a lower bound (excluding soy, a major feed component, some minor crops, several types of silage) estimate of agricultural land used for feeding livestock is $79.1 \times 0.57 + 8.4 \times 0.42 + 4.7 \times 0.33 + 4.4 + 62.3 + 60.0 \times 0.22 \approx 1.3 \times 10^8$ acres. This is roughly 6.9% of the total surface area of the contiguous 48 states, and to 12.6% of that surface area devoted to agriculture.

The land use efficiency of the animal-based portion of the diet may be estimated as follows. Averaged over 2000-05, the net mean American diet comprised 748 kcal person^{-1} day^{-1} from meat, eggs, nuts and dairy (37). To estimate, and subsequently eliminate, the contribution of nuts to this estimate, we note that during this period, the mean American consumed 6.3 lbs yr^{-1} peanuts and 3.1 lbs yr^{-1} tree nuts (37). Taking the total, 9.4 lbs person^{-1} yr^{-1} or 4272.7 gr person^{-1} yr^{-1}, to have a representative caloric intensity of 6,000 kcal kg^{-1}, nuts contributed $4.2727 \times 6,000/365.4 \approx 70$ kcal person^{-1} day^{-1}. Thus the animal-based part of the mean American diet was $748 - 70 = 678$ kcal person^{-1} day^{-1}. Considering the mean US population for this period, 289.6 million, this amounts to 7.17×10^{13} kcal yr^{-1} nationally. Given that the production of these products used at least 1.3×10^8 acres calculated above, the land use efficiency of the animal-based portion of the net mean American diet is $7.17 \times 10^{13}/1.3 \times 10^8 \approx 551,761$ kcal acre^{-1} yr^{-1}.

It is illuminating to compare the above land use efficiency of the animal-based portion of the net mean American diet to land-use efficiency of fruit, which contribute 80 kcal person^{-1} day^{-1}, or 8.47×10^{12} kcal yr^{-1} nationally, to the net mean American diet (37). Fruit tree plantations and orchards in the US occupied on average (over 2000-06) 3.13×10^6 acres (ref. 42, Table A-2). Therefore, the land use efficiency of fruit is $8.47 \times 10^{12}/3.13 \times 10^6 \approx 2,704,660$ kcal acre^{-1} yr^{-1}.

Dry beans provide another relevant example that may be, because of beans' high protein and fiber content and low glycemic index, more nutritionally interesting. Averaged over

2000-06, dry beans claimed 1.59×10^6 acres (43, Table 1). After accounting for all losses, this land supplied (2000-05 mean) 7 gr person^{-1} day^{-1}, or 2558 gr person^{-1} yr^{-1} (ref. 37, the Vegetables Table). Assuming the caloric value of dry beans to be 3.8 kcal gr^{-1}, this amounts to 9,464 kcals person^{-1} yr^{-1}, or to 2.74×10^{12} kcals yr^{-1} nationally. The mean US dry bean production thus supplies $2.74 \times 10^{12}/1.59 \times 10^6 \approx 1,723,270$ kcals acre^{-1} yr^{-1}.

In summary of the above calculations, land use for fruit and dry bean production is $2,704,660/551,761 \approx 5$ and $1,723,270/551,761 \approx 3$ times more efficient than land use for animal production. Thus as was shown above based on GHG emissions, land use considerations also suggest that the current US animal-based food production system is sub-optimal.

4 Summary and Main Conclusions

In this paper we strove to make the nutritional science community better aware of the extremely important geophysical corollaries of their findings as reflected in nutritional public recommendations.

We discussed in cursory details some geophysically significant consequences of food production, coastal ocean dead zones, some meteorological effects of agriculture, especially on surface reflectivity and the hydrological cycle, and greenhouse gas emissions.

Finally, based separately on greenhouse gas emissions and land use, we quantified the sub-optimality of the red meat component of the mean American diet.

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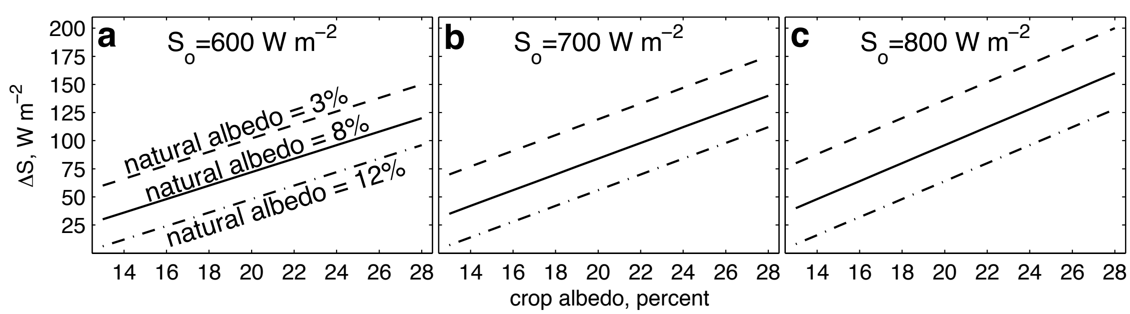

Figure 1: Changes in the surface radiative budget due to replacing natural ecosystems with crops as a function of crop albedo. Panels a, b and c show the changes assuming incoming solar radiation of 600, 700, and 800 W m^{-2}. In each panel, the dashed, solid, and dash-dotted lines correspond to assuming the natural environment the crops replaced had a characterisitc albedo of 3%, 8%, and 12%, respectively.