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

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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 and a clear environmental problem, and agriculture's effects on the surface heat budget. Both exemplify the unknown, complex and sometimes unexpected large-scale environmental effects of agriculture. We delineate the significant alignment in purpose between nutritional and environmental sciences. We identify red meat, and to a lesser extend the broader animal-based portion of the diet, as having the most environmental impact, with clear nutritional parallels.

Keywords: environment, geophysics, nutrition, agriculture

INTRODUCTION

In recent years, recognition of the substantial and 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 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 challenging, it is 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.

Why would nutritional science wish to concern itself with the environmental consequences of food production? 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 the section 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 individual dietary modifications stands to have enormous environmental benefits. Enhancing the likelihood of diet-mediated environmental improvements is the broader objective of this paper.

Some Geophysical Consequences of Food Production

While the scope of food production–geophysics interactions is extremely broad, including stream degradation, toxic effluent, air pollution, and water consumption, we will highlight two particularly complex and multi-faceted geophysical issues, ocean "dead zones" and agricultural effects on the surface heat balance and atmospheric structure.

"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). In essence the dead zone mechanism is as follows. Excessive fertilizer application, compounded with artificially enhanced water availability, 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 algal growth dramatically. 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 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). Second, many intensively cultivated regions are heavily "tiled." In its various forms, "tiling" strives to improve root system aeration by underlaying agricultural land with tiles 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 regions 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 substantially enhancing the local water available in large, contiguous, agricultural regions. Irrigation is not the largest contributor to this situation. Local recycling of precipitation, the supply of water vapor to the air column by re-evaporation already on the ground, is a more significant factor. Precipitation supplies water vapor to the lowermost atmosphere in a region. In many places, the lion's share of this supply is wind borne; when the wind transports more water vapor to a given location than it transports away from it, water vapor will rise over time. In some regions, another important source for future precipitation is local recycling of previously fallen precipitation.

Vegetation plays a similar role. Green leaves must open their stomata to take up atmospheric carbon dioxide (CO_2) required for photosynthesis. This results in evapo-traspiration, evaporative loss of leaf water vapor. Agriculture, especially row crops, has a similar—but artificially amplified—effect, since in many important agricultural regions these crops replace what would have otherwise been less lush vegetation. The result 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 cloud 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 not all of the precipitation rise is attributable to Mississippi Basin row crops, some as yet undetermined portion is (20).

All of these 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 less time water remains in the soil, the shorter and less complete is the processing of solutes, such as nutrients from unused fertilizer, by soil flora. The overall result is enhanced nutrient export at the expense of reduced local nutrient cycling. This suppression of local nutrient recycling and augmentation of nutrient export by acceleration of the hydrological cycle, compounded a 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.

Surface Reflectivity and Other Surface Exchanges

At the core of the global warming 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 by human activity—primarily the emission of CO_2 from fossil fuel energy consumption—is thought to be the primary vehicle of human-induced climate change. In this effect, 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 to the earth, thereby warming the surface. Because most GHGs 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 the fact that the variable most relevant to surface temperature is not the surface radiative budget, but the surface heat budget, which involves long wave radiation and other processes such as evaporative cooling. Even considering the surface radiative budget alone, rather than the heat budget, the key is not a particular contribution, but rather the overall balance, comprising both long and short wave (incoming solar) radiation, the latter being earth's climate main driver. So, while perturbing the earth's long wave radiative budget by enhanced atmospheric GHG concentrations from human activity is environmentally extremely important, the surface heat balance can be upset by other means. One of those means, modified surface reflectivity, is strongly linked with agriculture.

Surface reflectivity, or albedo, measures the portion of incoming solar radiation absorbed by—and thus available to warm—the surface. For example, the albedo of fresh snow is approximately 0.75, meaning that only 25% of the incoming solar radiation is absorbed by the surface, while 75% of it is reflected back up from the surface. Natural ecosystem agriculture is typically characterized by reflectivity 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 albedo changes due to agriculture, where S_o is the incoming solar flux in W m^{-2}, and $\square S = S_o (\square_{crop} - \square_{nat})$ is the change in absorbed solar flux due to cropland with albedo ($\square_{crop}$) replacing a natural ecosystem albedo ($\square_{nat}$). 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 (the right side of the panel), 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, there is no incoming solar radiation), and, more importantly, only areas in which cropland exists and replaces a natural low albedo surface. 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 heat of a modest □S of, say, 70 W m^{-2},

$$\square\ (\square T_{\text{soil}}) = \frac{\square \mathrm{S}}{\square\ \mathrm{c}_p\ h}\ \square \mathrm{t} \approx 1\ \mathrm{K} \qquad \text{equation 1}$$

where K denotes degrees Kelvin. In equation 1 (E1), $\square T_{\text{soil}}$ denotes soil solar warming over a time span □t = 4 hours, representing, soil warming between 8AM and noon. Therefore, this formula gives the change in soil warming by the sun over 4 hours. The albedo change yields the solar heating change □S. Other terms in the equation are soil density (□ = 10^3 kg m^{-3}), 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. We will single out for a brief discussion one of those – deepening (thickening) 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 E1, 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 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 where 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; the more vigorous the flow, the more turbulent the 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, 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. All else being constant, a given water vapor source will saturate the boundary layer, 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.

In summary, embedding agricultural land within natural landscapes changes the surface reflectivity of 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 these processes strongly affect, and are affected by, agriculture.

Energy Consumption and Greenhouse Gas Emissions

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

Agriculture and food production use fossil fuel energy, which produce emissions of CO_2, and 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 (30, Table ES-2), energy use in agriculture amounts to emissions of

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

where the US population in 2006 is rounded up from the US Census Bureau (31, Table T1). Note that the effects of the minor omissions and simplifications of this estimate 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; different 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 force 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 (30, Table 6-1), or

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[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.

$$^{e}\text{non CO}_2 = \frac{618.9 \cdot 10^6 \text{ ton CO}_2\text{ - eq}}{299 \cdot 10^6 \text{ Americans}} \approx 2.07 \; \frac{\text{ton CO}_2\text{ - eq}}{\text{person} \times \text{yr}} \qquad \text{equation 3}$$

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

$$^{e}\text{total CO}_2 \leq {}^{e}\text{CO}_2 + {}^{e}\text{non CO}_2 = 3.96 \; \frac{\text{ton CO}_2\text{ - eq}}{\text{person} \times \text{yr}} \qquad \text{equation 4}$$

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

$$^{E}\text{all} = \frac{6318.9 \cdot 10^6 \text{ ton CO}_2\text{ - eq}}{299 \cdot 10^6 \text{ Americans}} \approx 21.13 \; \frac{\text{ton CO}_2\text{ - eq}}{\text{person} \times \text{yr}} \qquad \text{equation 5}$$

of which food production is about 19%.

Some Effects of Nutritional Science on the Geophysical Consequences of Agriculture

There is a significant alignment between diet modifications guided by better nutrition, and those guided by geophysical prudence; what is good for one's health is often also geophysically and environmentally beneficial and desirable.

The single most important example of the above alignment is red meat consumption. The human health costs of red meat consumption are well established (32-35). As a result, the government-independent nutrition 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.

Red Meat Production 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 (CONVERT TO kg), this amounts to

$$244.5 \frac{\text{red meat kcal}}{\text{person} \times \text{day}} \; 365.4 \frac{\text{day}}{\text{yr}} \; \frac{73.3\ \text{kg}}{47.3\ \text{kg}} \approx 138{,}507.44 \frac{\text{red meat kcal}}{\text{person} \times \text{yr}} \qquad \text{equation 6}$$

where 73.3 kg and 47.3 kg 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 creates 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, manure management, and the production of nitrous oxides released during growing feed. 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% (38, Table 3). The value means that a variety of fossil fuels is consumed during the course of producing 100 calories of edible red meat. The national mean red meat consumption therefore entails consumption of 138, 507/0.093 = 1, 489, 327 fossil fuel kcals person^{-1} 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

$$1{,}489{,}327 \frac{\text{Fossil fuel kcals}}{\text{person} \times \text{yr}} \times 0.2778 \frac{\text{gr } CO_2}{\text{fossil fuel kcal}} \times \frac{1\ \text{gr}}{10^3\ \text{kg}} \approx 413.73 \frac{\text{kg } CO_2}{\text{person yr}} \qquad \text{equation 7}$$

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 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)$^{-1}$ (5, Table 5). Note again that we ignore the nitrous oxides emitted during the production of feed, rendering our calculation a lower bound. 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 × 0.57 + 1.52 × 0.42 + 2.82 × 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

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

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 413.73 + 840.74 = 1, 254.47 kg CO-eq person^{-1} yr^{-1}.

Referring to calculations presented earlier in this paper, this annual per capita emission amounts to 100 × 1.25447/3.96 ~ 32% of the per capita dietary GHG footprint, and 100 × 15 1.25447/21.13 ~ 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.

The Need for Land

The intensity of geophysical consequences of food production is proportional to the surface area dominated by agriculture; the more land used for growing food, the more ubiquitous these effects. While there are various ways by which dietary choices affect demand for land, below we single out the key issue, grain production for animal feed.

Of the surface area of the United States, excluding Alaska and Hawaii, about 1,026 million acres, or over 54% of the total, was devoted to agriculture in 2002 (38). Crops alone occupied 442 million acres, ~ 23% (38). Averaged over 2000-06, corn, sorghum, barley and oats consumed 79.1, 8.4, 4.7 and 4.4 million acres each (39). 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 ~ 22% is used for feed (40)—occupied ~ 60 million acres. Thus a lower bound estimate (excluding soy, a major feed component, some minor crops, several types of silage) of agricultural land used for feeding livestock is $79.1 \times 0.57 + 8.4 \times 0.42 + 4.7 \times 0.33 + 4.4 + 62.3 + 60.0 \times 0.22 \sim 1.3 \times 10^8$ acres. This is roughly 6.9% of the total surface area of the continental United States, and 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 $4.2727 \times 6,000/365.4 \sim 70$ kcal person^{-1} day^{-1}. Thus the animal-based part of the mean American diet was 748 - 70 or 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 $7.17 \times 10^{13}/1.3 \times 10^{8} \sim 551, 761$ 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 estimated above 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 (42, Table A-2). Therefore, the land use efficiency of fruit is $8.47 \times 10^{12}/3.13 \times 10^{6}$, roughly equal to 2.7×10^{6} kcal acre^{-1} yr^{-1}.

Dry beans provide another relevant example that, because of the high protein and fiber content and low glycemic index of beans, may be more nutritionally interesting. Averaged over 2000-06, dry beans claimed 1.59×10^{6} acres (42, 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} (37, the Vegetables Table). Assuming the caloric value of dry beans to be 3.8 kcal/gr^{-1}, this amounts to 9,464 kcal person^{-1} yr^{-1}, or to 2.74×10^{12} kcal yr^{-1} nationally. The mean US dry bean production thus supplies $2.74 \times 10^{12}/1.59 \times 10^{6}$, roughly equal to 1.7×10^{6} kcal acre^{-1} yr^{-1}.

In summary of the above calculations, land use for fruit and dry bean production is $2.7\times 10^{6}/551{,}761 \approx 5$ and $1.7 \times 10^{6}/551, 761 \approx 3$ times more efficient than land use for animal production. Thus, based on GHG emissions, land use considerations also suggest that the current US animal-based food production system is sub-optimal.

CONCLUSIONS

In this paper, we strive to make the nutrition science community better aware that there are extremely important geophysical corollaries of their findings as reflected in public nutrition recommendations. We discuss some geophysically significant consequences of food production, including coastal ocean dead zones, some meteorological effects of agriculture, especially on surface reflectivity and the hydrological cycle, and greenhouse gas emissions. Finally, based on greenhouse gas emissions and land use, we quantify the sub-optimality of the red meat component of the mean American diet.

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REFERENCES

1. Daily G, Dasgupta P, Bolin B, Crosson P, Guerny J, Ehrlich P, Folke C, Jansson AM, Jansson BO, Kautsky N, Kinzig A, Levin S, Maler KG, Pinstrup-Andersen P, Siniscalco D, Walker B. Food production, population growth, and the environment. Science 1998;281:1291-2.
2. Conway G. The double green revolution: Balancing food, poverty and environmental needs in the 21st century. In: Lee DR, Barrett CB, eds. Tradeoffs or synergies?: Agricultural intensification, economic development and the environment, Wallingford, Oxfordshire, UK: CABI Publishing, 1998:17-34.
3. Zhu1 ZL, Chen DL. Nitrogen fertilizer use in China - Contributions to food production, impacts on the environment and best management strategies. Nutrient Cycling in Agroecosystems 2002;63:117-27.
4. Pollan M. The Omnivore's Dilemma: A Natural History of Four Meals. New York: Penguin, 2006.
5. Eshel G, Martin PA. Diet, energy and global warming. Earth Interactions 2006;10:1-17.
6. Vandana S. Stolen Harvest. Cambridge, MA: South End Press, 2000.
7. Pimental D. Population growth and the environment: Planetary stewardship. Electronic Green Journal 1998;9.
8. Nestle M. Food politics: How the food industry influences nutrition and health. Berkeley: University of Californai Press, 2002.
9. Epstein BE, Quatromoni PA, Franz MM, Cupples LA, Copenhafer DL, Millen BE. Comparisons of adherence to national dietary guidelines among younger and older adults. The Framingham Nutrition Studies, 1991-1995. Journal of the American Dietetic Association 1997; 97:A57.

10. Millen BE, Quatromoni PA, Franz MM, Epstein BE, Cupples LA, Copenhafer DL. Population nutrient intake approaches dietary recommendations 1991 to 1995 Framingham nutrition studies. Journal of the American Dietetic Association 1997; 97:742-9.
11. Malakoff D. Death by suffocation in the Gulf of Mexico. Science 1998,281:190-192.
12. Howarth R, Anderson D, Cloern J, Elfring C, Hopkinson C, Lapointe B, Malone T, Marcus N, McGlathery K, Sharpley A, Walker D. Nutrient pollution of coastal rivers, bays, and seas. Issues in Ecology 2000; 7.
13. Joyce S. The dead zones: Oxygen-starved coastal waters. Environmental Health Perspectives 2000;108:120-5.
14. Lindstrom MJ, Schumacher TE, Cogo NP, Blecha ML. Tillage effects on water runoff and soil erosion after sod. Journal of Soil and Water Conservation 1998;53:59-63.
15. Sauer TJ, Daniel TC. Effect of tillage system on runoff losses of surface-applied pesticides. Soil Science Society of America Journal 1987;51:410-5.
16. Neilsen GH, Culley JL, Cameron DR. Nonpoint N runoff from agricultural watersheds into the Great Lakes. Journal of Great Lakes Research 1980; 6:195-202.
17. Betts RA. Integrated approaches to climate-crop modelling: Needs and challenges. Philosophical Transactions of The Royal Society B 2005;360:2049-65.
18. Lyons TJ. Clouds form preferentially over native vegetation. Proceedings of The International Environmental Modelling and Software Society conference, June 24-27 2002, Lugano, Switzerland, Vol. 2:355-9.
19. Milly PCD, Dunne KA. Trends in evaporation and surface cooling in the Mississippi River basin. Geophysical Research Letters 2001;28:1219-22.
20. Betts AK, Ball JH, Bosilovich M, Viterbo P, Zhang YC, Rossow WB. Intercomparison of

water and energy budgets for five Mississippi subbasins between ECMWF reanalysis (ERA-40) and NASA Data Assimilation Office fvGCM for 1990-1999. Journal of Geophysical Research-Atmospheres 2003;108:8618.

21. Burba GG, Verma SB. Prairie growth, PAR albedo and seasonal distribution of energy fluxes. Agricultural and Forest Meteorology 2001;107:227-40.
22. Betts AK, Ball JH. Albedo over the boreal forest. Journal of Geophysical Research 1997;102 (D24) :28901-10.
23. Stanhill G, Cox JTH, Moreshet S. The Effect of Crop and Climatic Factors on the Radiation Balance of an Irrigated Maize Crop. The Journal of Applied Ecology 1968;5:707-20.
24. Impens I, Lemeur R. The radiation balance of several field crops. Theoretical and Applied Climatology 1969;17:261-8.
25. Wigley TML. The climate change commitment. Science 2005;307:1766-9.
26. Stull RB. An introduction to boundary layer meteorology. Dordrecht, The Netherlands: Kluwer, 1988.
27. Heagle AS. Ozone and crop yield. Annual Review of Phytopathology 1989;27:397-423.
28. Heller MC, Keoleian GA. Life cycle-based sustainability indicators for assessment of the U.S. food system. Ann Arbor, MI: Center for Sustainable Systems, University of Michigan, 2000: 42.
29. Horrigan L, Lawrence RS, Walker P. How sustainable agriculture can address the environmental and human health harms of industrial agriculture. Environmental Health Perspectives 2002;110:445-56.
30. United States Environmental Protection Agency. U.S. Greenhouse gas inventory reports, February 2008, http://www.epa.gov/climatechange/emissions/usinventoryreport.html

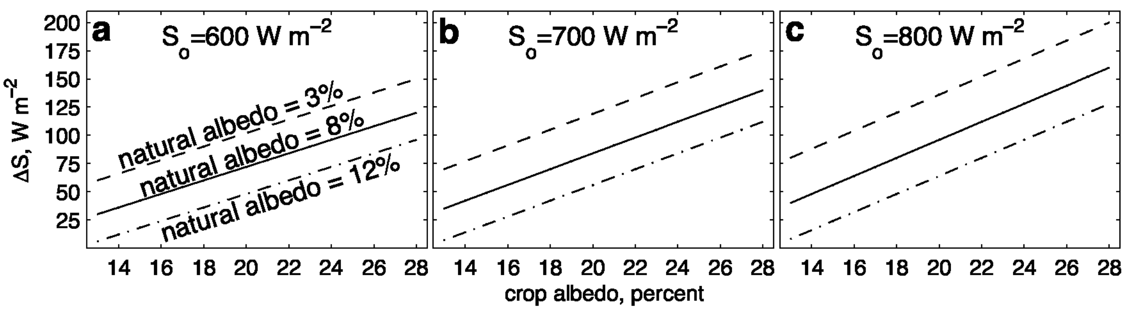
31. United States Census Bureau. American FactFinder, 2007 Population Estimates.
32. Willett WC. Eat, drink and be healthy. New York: Simon & Schuster Source, 2001.
33. Song Y, Manson JE, Buring JE,, Liu S. A prospective study of red meat consumption and type 2 diabetes in middle-aged and elderly women. Diabetes Care 2004;27:2108-15.
34. Sandhu MS, White IR, McPherson K. Systematic review of the prospective cohort studies on meat consumption and colorectal cancer risk. Cancer Epidemiology Biomarkers & Prevention 2001;10:439-46.
35. Chao A, Thun MJ, Connell CJ, McCullough ML, Jacobs EJ, Flanders WD, Rodriguez C, Sinha R, Calle EE. Meat consumption and risk of colorectal cancer. The Journal of the American Medical Association 2005;293:172-82.
36. Campbell TC, Campbell TM. The China study. Dallas, Texas: Benbella, 2004.
37. United States Department of Agriculture, Economic Research Service. Food Availability (supply and disappearance). http: //www.ers. usda.gov/ Data/FoodConsumption/ FoodAvailIndex. htm
38. Lubowski RN, Vesterby M, Bucholtz S, Baez A, Roberts MJ. Major uses of land in the United States, 2002. United States Department of Agriculture, Economic Research Service. 2002/EIB-14.
39. United States Department of Agriculture, Economic Research Service. Feed Grains Database: Yearbook tables, 2007.
40. United States Department of Agriculture, Economic Research Service. Wheat Yearbook 2006.
41. United States Department of Agriculture, Economic Research Service. Fruit and Tree Nut Yearbook, October 2007.

42. United States Department of Agriculture, Economic Research Service. Dry Bean Book, September 2007, USDA Document Number 86003.

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 represent an assumption that the natural environment replaced by crops had a characteristic albedo of 3%, 8%, and 12%, respectively.

Figure 1


a
S_o=600 W m^{-2}
b
S_o=700 W m^{-2}
c
S_o=800 W m^{-2}
natural albedo = 3%
natural albedo = 8%
natural albedo = 12%
ΔS, W m^{-2}
200
175
150
125
100
75
50
25
14
16
18
20
22
24
26
28
crop albedo, percent