The American Journal of Clinical Nutrition

Geophysics and nutritional science: toward a novel, unified paradigm[1–3]

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ABSTRACT

This article discusses 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, which are at the confluence of oceanography, aquatic chemistry, and agronomy and which are a clear environmental problem, and agriculture's effects on the surface heat budget. These 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 extent the broader animal-based portion of the diet, as having the greatest environmental effect, with clear nutritional parallels. *Am J Clin Nutr* 2009;89(suppl):1710S–6S.

INTRODUCTION

In recent years, recognition of the substantial and expanding deleterious environmental consequences of food production has been steadily expanding among the scientific community and among 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, multidisciplinary, 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 multifaceted, carving a niche at the confluence of many fields of inquiry. As such, the successful treatment of food-environment interactions requires a dialog across traditional disciplinary boundaries. Although initiating and sustaining such a dialog is challenging, it is potentially highly influential, because successful transdisciplinary collaboration will bring a multitude of backgrounds, skills, talents, and styles to address the problem. The purpose of this article is to further a subset of the necessary dialog, that between geophysics and nutritional sciences.

Why should nutritional science concern itself with the environmental consequences of food production? Nutritional science plays a central role in shaping food-environment interactions and is thus 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 (discussed briefly below) because 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 diets. Enhancing the likelihood of diet-mediated environmental improvements is the broader objective of this article.

SOME GEOPHYSICAL CONSEQUENCES OF FOOD PRODUCTION

Although the scope of interactions between food production and geophysics is broad and includes, eg, stream degradation, toxic effluent, air pollution, and water consumption, we highlight 2 particularly complex and multifaceted geophysical issues: ocean "dead zones" and agricultural effects on the surface heat balance and atmospheric vertical 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 shellfish 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 dead zone mechanism can be abbreviated 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 sun-

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First published online April 8, 2009; doi: 10.3945/ajcn.2009.26736BB.

Am J Clin Nutr 2009;89(suppl):1710S–6S. Printed in USA. © 2009 American Society for Nutrition

light is abundant, the foundation of the oceanic food web—algal primary productivity (photosynthesis)—is limited mostly by nutrient availability. Consequently, the added nutrient that the leached fertilizer introduces into the ocean enhances algal growth dramatically. On death of the short-lived algae, this excess organic matter decomposes in the water column and, near the bottom, follows a chemical reaction that, like breathing, can be described as reversed photosynthesis. This decomposition consumes oxygen dissolved in the seawater, suppressing its ambient levels to below those necessary for many ocean life forms, causing die-offs.

There are important contributions from agriculture to the dead zone problem. Fertilizer application on fields in the drainage basin is the most straightforward. In addition, agriculture accelerates the hydrologic 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 semipermeable pipes that accelerate the flow of subsurface water toward ditches and streams (16). Finally, the surface drainage system—the network of creeks, streams, and rivers—of 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 an important contributor to this situation, as is local recycling of precipitation, the re-evaporation of precipitated water already on the ground.

Vegetation plays a similar role. Green leaves must open their stomata to take up atmospheric carbon dioxide required for photosynthesis. This results in the evaporative loss of leaf water vapor. Agriculture, especially row crops, has a similar, but artificially amplified, effect, because in many important agricultural regions these crops replace what otherwise would have 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, most notably cooling the surface (17) and modifying cloud patterns (18).

A quantitative example of the overall change resulting from these processes is Milly and Dunne's estimate (19) that human-induced evapotranspiration (plant-mediated evaporation) in the Mississippi Basin enhanced natural evaporation by 12 $\text{mm} \cdot \text{y}^{-1}$ during the final decades of the 20th century and that this evaporation augmentation is rising at a rate of 2.6 $\text{mm} \cdot \text{y}^{-1}$, or 22%, per decade. For the same period, the authors also report a precipitation increase rate of ~18 $\text{mm} \cdot \text{y}^{-1}$ per decade. Although not all of the precipitation rise is attributable to row crops, some (as yet undetermined) portion clearly is (20).

All of these hydrologic 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, eg, 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 hydrologic cycle, compounded by a vastly enhanced nutrient supply, is not only a centerpiece of the dead zone mechanism but also, arguably, is among the 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, which is the balance between incoming (downward) and outgoing (upward) surface heat fluxes. In most popular and scientific accounts, the focus is the modification of the natural greenhouse effect by human activity, primarily the emission of carbon dioxide from fossil fuel energy consumption. In this effect, greenhouse gases (GHGs), eg, carbon dioxide and methane, absorb some long-wave radiation emitted upward by the earth surface and radiate the absorbed energy back down, thereby warming the surface. Because most GHGs absorb long-wave radiation but are neutral with respect to shortwave (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, eg, evaporative cooling. Even considering the surface radiative budget alone, ignoring the broader budget, the key is not a particular contribution but the overall balance comprising long- and shortwave (incoming solar) radiation (the latter being earth's main climate driver). Although perturbing the earth's long-wave radiative budget by enhanced atmospheric GHG concentrations from human activity is important, the surface heat balance can be upset by other means. One of those means, modified surface reflectivity, is strongly linked to agriculture.

Surface reflectivity, or albedo, measures the portion of incoming solar radiation reflected by, and thus unavailable to warm, the surface. For example, the albedo of fresh snow is ~0.75, meaning that only 25% of the incoming solar radiation is absorbed by the surface, whereas 75% of it is reflected back up from the surface. Natural ecosystem agriculture replaces are typically characterized by reflectivity in the 3–12% range (21, 22). In contrast, summer crop reflectivity is typically in the 13–28% range (23, 24). As shown in **Figure 1**, agriculture-related albedo changes [the transition from (α_{nat} to α_{crop}), where "crop" is cropland albedo and "nat" is natural ecosystem albedo], can have dramatic heat flux consequences, given by $\Delta S = S_{\text{o}} (\alpha_{\text{crop}} - \alpha_{\text{nat}})$, where S_{o} is the incoming solar flux in $\text{W} \cdot \text{m}^{-2}$. The perturbations of the surface radiative budget are large. For example, at the beginning of a season, when the crop is young and its albedo correspondingly large (the right side of the panel), a midday perturbation (when the incoming solar flux can readily reach 800 $\text{W} \cdot \text{m}^{-2}$; *see* Figure 1C) is ~200 $\text{W} \cdot \text{m}^{-2}$. This is a staggering perturbation, ~50 times larger than the corresponding ~4 $\text{W} \cdot \text{m}^{-2}$ perturbation of the surface long-wave budget due to doubling of atmospheric carbon dioxide (25). Note that the differences in Figure 1 represent only daytime (since at night

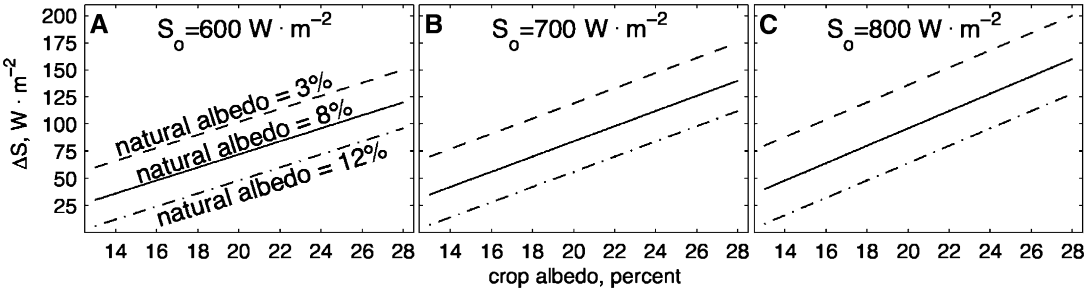

FIGURE 1. Changes in the surface radiative budget due to replacing natural ecosystems with crops as a function of crop albedo (surface reflectivity, ie, the fraction of incoming downward solar radiation that is reflected before being absorbed by the surface). Changes shown assume incoming solar radiation of (A) 600, (B) 700, and (C) 800 W · m^{-2}, respectively. The dashed, solid, and dashed-dotted lines represent an assumption that the natural environment replaced by crops had a characteristic albedo of 3%, 8%, and 12%, respectively.

there is no 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 carbon dioxide and other GHGs prevails at all times throughout the earth's surface.

Notwithstanding the stipulations stated above, the message of Figure 1 is important. First, locally, the shortwave 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 magnitude comparable to those resulting from doubling of atmospheric carbon dioxide (17, 25).

It is instructive to show the change in surface heating rates of a modest ΔS of ~70 W · m^{-2}:

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

where K denotes degrees Kelvin and δT_{soil} denotes soil solar warming over a time span δt = 4 h, representing, eg, soil warming between 0800 and 1200, where the albedo change yields the solar heating change ΔS. Other terms in Equation *1* are soil density ($\rho = 10^3 \cdot \text{kg} \cdot \text{m}^{-3}$), specific heat at constant pressure ($c_p = 10^3\ \text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), and the thickness ($h$ = 3 m) of the thermally active soil layer. Whereas a heating rate difference of 1 K (4 h)$^{-1}$ is significant for numerous atmospheric processes, we single out one of those for a brief discussion: deepening (thickening) of the atmospheric boundary layer due to wind generation by thermal gradients and turbulence generation by those winds.

The importance of the process captured by the above calculation is its ability to give rise to thermal gradients, which can set air in motion. Consider, for example, 2 hypothetical adjacent land parcels, one covered with forest and the other with young corn. If their soil temperatures are assumed the same at 0800, according to Equation *1*, by 1200 the corn field is 1-K cooler than the forest. This thermal difference accelerates air, creating wind. If the 2 plots are close enough to each other, the winds between them quickly become vigorous.

Next, let us introduce the boundary layer, the lowermost and environmentally most important part of the atmosphere (26). Airborne pollutants and evaporated surface water, among other trace constituents of surface origin, initially collect in the boundary layer, from which they are redistributed higher in the atmosphere by mostly sluggish vertical exchange processes.

The depth of the boundary layer—its surface-to-ceiling vertical extent—is calculated by taking note of various processes, eg, the rate of turbulence generation by boundary layer winds; the more vigorous the flow, the more turbulent the fluid. All other factors assumed equal, the more turbulent the boundary layer, the deeper it gets, thus the larger the atmospheric container in which various trace constituents of surface origin collect. Boundary layer depth is therefore 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 equal, a deeper boundary layer results in lower relative humidity and elevated evaporation from agricultural and nonagricultural surfaces. Similarly, all other factors assumed equal, a given water vapor source saturates the boundary layer and thus stops evaporation twice as fast if the boundary layer depth is halved. Boundary layer depth is also 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, an important GHG.

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 GHG 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 produces emissions of carbon dioxide and small amounts of other GHGs. Quantitative estimates of energy use in food production vary widely. In the United States, the total energy use for food production is estimated to fall in the range of ~10–17% of the total energy consumption (28, 29). Assuming a conservative 10% and using total US carbon dioxide emissions from fossil fuel combustion of 5639.4 Tg (terragram, a million metric tons)/y in

2006) (30, Table ES-2), energy use in agriculture amounts to emissions of

$$e_{\mathrm{CO_2}} = \frac{5639.4 \cdot 10^6 \text{ ton CO}_2 \times 0.1}{299 \cdot 10^6 \text{ Americans}} \approx 1.89 \frac{\text{ton CO}_2}{\text{person} \times \text{y}} \qquad (2)$$

where the US population in 2006 is estimated from US Census Bureau data (31, Table T1). The minor omissions and simplifications of this estimate all have effects of the same sign, rendering the above estimate a lower bound. One challenge to this statement may be that summing the direct (on-farm) and ammonia fertilizer production energy uses yields only ~1% of the total US GHG emissions as a result of energy use. We chose the value of 10%, which we consider low, because estimates on the basis of full life cycle analyses (28, 29) are more complete than the simple addition (described above).

In addition, agriculture, especially animal farming, results in significant emissions of 2 powerful non–carbon dioxide GHGs, methane and nitrous oxide. Each of these gases has a different radiative effect—different from each other and from carbon dioxide. To facilitate addition of their radiative effects on earth's surface temperatures, emissions of non–carbon dioxide GHGs are expressed as carbon dioxide equivalent (CO_2-eq), the mass of carbon dioxide 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. Combined agricultural 2006 emissions of methane and nitrous oxide were 618.9 Tg CO_2-eq (30, Table 6-1), or, on a per capita basis,

$$e_{\mathrm{non\,CO_2}} = \frac{618.9 \cdot 10^6 \text{ ton CO}_2\text{-eq}}{299 \cdot 10^6 \text{ Americans}} \approx 2.07 \frac{\text{ton CO}_2}{\text{person} \times \text{y}} \qquad (3)$$

A conservative lower-bound estimate of total food production related greenhouse gas (GHG) emissions therefore is as follows:

$$e_{\mathrm{total}} \geq e_{\mathrm{CO_2}} + e_{\mathrm{non\,CO_2}} = 3.96 \frac{\text{ton CO}_2\text{-eq}}{\text{person} \times \text{y}} \qquad (4)$$

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

$$E_{\mathrm{all}} = \frac{6318.9 \cdot 10^6 \text{ ton CO}_2\text{-eq}}{299 \cdot 10^6 \text{ Americans}} \approx 21.13 \frac{\text{ton CO}_2\text{-eq}}{\text{person} \times \text{y}} \qquad (5)$$

of which food production is ~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 this 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 reduced red meat consumption (32, 36). Similar conclusions can be reached on the basis of geophysical considerations, principally GHG emissions.

Red meat production and GHG emissions

From 2000 to 2005, the average American ingested ~244.5 red meat · kcal · d^{-1} (37). Given the substantial losses of meat along the distribution chain, this amounts to

$$244.5 \frac{\text{red meat kcal}}{\text{person} \times \text{d}} 365.4 \frac{\text{d}}{\text{y}} \frac{73.3 \text{ kg}}{47.3 \text{ kg}} \approx 138,507.44 \frac{\text{red meat kcal}}{\text{person} \times \text{y}} \qquad (6)$$

where 73.3 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 conceived of as the consumption amplification factor resulting from losses during distribution to consumers of meat that already has incurred the full environmental costs of production.

The production of this amount of meat results in carbon dioxide and non–carbon dioxide GHG emissions, the former mostly the result of fossil fuel energy consumption and the latter mostly the result of anaerobic organic matter decomposition associated with ruminant digestion, manure management, and the production of nitrous oxides released by growing feed. To quantify carbon dioxide emissions resulting from 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 national red meat consumption, therefore, entails consumption of ~138,507/0.093 ≈ 1,489,327 fossil fuel kcal · person^{-1} · y^{-1}. To convert these amounts to carbon dioxide emissions, we use a conversion factor derived from the total US economy emissions and energy consumption (37), 0.2778 g carbon dioxide (fossil fuel $\text{kcal})^{-1}$. Using this conversion factor, fossil fuel energy required to sustain the national red meat consumption amounts to the emissions of

$$\begin{aligned} 1,489,327 \frac{\text{fossil fuel kcal}}{\text{person} \times \text{y}} \times 0.2778 \frac{\text{g CO}_2}{\text{fossil fuel kcal}} \times \frac{1 \text{ kg}}{10^3 \text{ g}} \\ \approx 413.73 \frac{\text{kg CO}_2}{\text{person} \times \text{y}} \end{aligned} \qquad (7)$$

Next, we turn our attention to emissions of non–carbon dioxide GHGs associated with the red meat portion of the American diet. For each meat type we use a non–carbon dioxide emission factor, the mass of carbon dioxide that would cause the same radiative forcing as the actual amounts of methane and nitrous oxides emitted in the course of producing every kilocalorie of meat. The non–carbon dioxide emission factors we use for beef, pork, and lamb are, respectively, 9.48, 1.52, and 2.82 g CO_2-eq (meat $\text{kcal})^{-1}$ (5, Table 5). Again, we ignore the nitrous oxides emitted during the production of feed, rendering our estimate a lower bound. Deviating from our earlier work to reflect more recent national meat consumption statistics, we assume the national red meat mixture to comprise 57% beef, 42% pork, and 1% lamb (37). The weighted non–carbon dioxide emission factor appropriate for the red meat portion of the national diet, therefore, is ~$9.48 \times 0.57 + 1.52 \times 0.42 + 2.82 \times 0.01 = 6.07$ g CO_2-eq (meat $\text{kcal})^{-1}$. The emissions of non–carbon dioxide GHGs associated with production of the red meat portion of the national diet, therefore, are as follows:

$$138,507.44\,\frac{\text{red meat kcal}}{\text{person}\times\text{y}}\,6.07\,\frac{\text{g CO}_2\text{-eq}}{\text{red meat kcal}} = 840.74\,\frac{\text{kg CO}_2\text{-eq}}{\text{person}\times\text{y}} \qquad (8)$$

In summary, the total (energy-related carbon dioxide plus non–carbon dioxide) GHG emissions associated with producing the red meat portion of the national diet are 413.73 + 840.74 = 1254.47 kg CO_2-eq · person^{-1} · y^{-1}.

Referring to calculations discussed earlier in this article, this annual per capita emission amounts to 100 × 1.25447/3.96, or ~32% of the per capita dietary GHG footprint, and 100 × 1.25447/21.13, or ~6% of the per capita overall GHG footprint. With a net ingested caloric input in the mean American diet during 2000–2005 of ~2704 kcal · person^{-1} · d^{-1} (37), the red meat portion, 244.5 kcal · person^{-1} · d^{-1} (37), is calorically only 9%, yet it accounts for 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. Although there are various ways by which dietary choices affect demand for land, we single out a key issue, grain production for animal feed.

Of the total surface area of the United States, excluding Alaska and Hawaii, ~1026 million acres (>54%) was devoted to agriculture in 2002 (38). Crops alone occupied 442 million acres, or ~23% (38). During 2000–2006, corn, sorghum, barley, and oats consumed ~79.1, 8.4, 4.7, and 4.4 million acres, respectively (39), while the portions of those crop yields used for animal feed were 57%, 42%, 33%, and ~100%, respectively. In addition, hay production over the same period used ~62.3 million acres and wheat production—of which ~22% is used for feed (40, 41)—occupied ~60 million acres. Thus, a lower-bound estimate (excluding soy, a major feed component; some minor crops; and several types of silage) of agricultural land used for feeding livestock is 79.1 × 0.57 + 8.4 × 0.42 + 4.7 × 0.33 + 4.4 + 62.3 + 60.0 × 0.22 ≈ 1.3 × 10^8 acres. This is ~6.9% of the total surface area of the continental United States and 12.6% of the surface area devoted to agriculture.

The land-use efficiency of the animal-based portion of the diet may be estimated as follows: from 2000 to 2005, the mean American diet comprised ~748 kcal · person^{-1} · d^{-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 American diet included ~2.86 k · y^{-1} peanuts and 1.41 k · y^{-1} tree nuts (37). Assuming that the total, 4.2727 kg · person^{-1} · y^{-1}, has a representative caloric intensity of 6000 kcal kg^{-1}, nuts contributed 4.2727 × 6000/365.4 ≈ 70 kcal · person^{-1} · d^{-1}. Thus, the animal-based part of the mean American diet was ~748 − 70 or ~678 kcal · person^{-1} · d^{-1}. Considering the mean US population for this period, ~289.6 million, this amounts to 7.17 · 10^{13} · kcal · y^{-1} nationally. Given that the production of these calories used ≥1.3 ×10^8 acres (calculated above), the land-use efficiency of the animal-based portion of the American diet is ~7.17 × 10^{13}/1.3 × 10^8 ≈ 551,761 kcal · acre^{-1} · y^{-1}.

It is illuminating to compare the land-use efficiency of the animal-based portion of the mean American diet (estimated above) with land-use efficiency of fruit (which contributes 80 kcal · person^{-1} · d^{-1} or 8.47 · 10^{12} kcal · y^{-1} nationally) to the mean American diet (37). Fruit tree plantations and orchards in the United States occupied (between 2000 and 2006) ~3.13 × 10^6 acres (42, Table A-2). Therefore, the land-use efficiency of fruit is 8.47 × 10^{12}/3.13 × 10^6 ≈ 2.7 × 10^6 kcal · acre^{-1} · y^{-1}.

Dry beans provide another relevant example that, because of their high protein and fiber content and low glycemic index, may be nutritionally interesting. Between 2000 and 2006, dry beans claimed ~1.59 × 10^6 acres (42, Table 1). After accounting for all losses, this land supplied (during 2000–2005) ~7 g · person^{-1} · d^{-1} or ~2558 g · person^{-1} · y^{-1} (37, Vegetables Table). Assuming the caloric value of dry beans is 3.8 kcal g^{-1}, this amounts to 9720 kcal · person^{-1} · y^{-1} or 2.81 × 10^{12} kcal y^{-1} nationally. The US dry bean production land use efficiency is therefore ~2.81 × 10^{12}/1.59 × 10^6, which is equal to ~1.8 × 10^6 kcal · acre^{-1} · y^{-1}.

To summarize the above calculations, land use for fruit and dry bean production is 2.7 × 10^6/551,761 and 1.8 × 10^6/551,761, or ~5 and ~3 times, respectively, more efficient than land use for animal production. Thus, in addition to GHG considerations, land-use efficiency also suggests that the current US animal-based food production system is suboptimal.

CONCLUSIONS

In this article, we strive to make the nutrition science community better aware of some of the 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 meteorologic effects of agriculture, especially on surface reflectivity and the hydrologic cycle; and GHG emissions. Finally, on the basis of GHG emissions and land use, we quantify the suboptimality of the red meat component of the mean American diet. (Other articles in this supplement to the Journal include references 43–69.)

Neither author had a conflict of interest.

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