Perspectives

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Nourishing Earth, Nourishing Ourselves

Part 2: Chefs, Diets, Ecological Doctors, Fossil Fuels, and Changing Climates

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Abbreviations

BW	**Body weight**
GHGE	**Greenhouse gas emissions**

Abstract

Homo sapiens have lived on Earth for roughly 300,000 years. Our ancestors were hunters and gatherers who used hundreds of plants and animals for food, medicine, clothing, and shelter. Only in the past 10,000 years did we transition from hunters and gatherers to pastoralists and small-scale farmers and ranchers. And only during the past century did we create civilizations reliant on industrial agriculture and fossil fuels. In the process, we transformed from sunlight-driven ecological economies linked with the landscapes that once nourished and sustained us to money-centric economies disconnected from nature and dependent on fossil fuels. Diet, human, and environmental health are now topics of great contention, but the terrain that links food production and nutrition with human and planetary health is not as simple as a holy war of plant vs meat eaters. Most humans are omnivores, and given the diversity of settings people inhabit, one-size-fits-all approaches to diets are bound to fail. We must value the many ways people sustain themselves globally and consider the vital roles plants and animals play in nourishing human and environmental health on a warming planet. If the projected lack of oil and natural gas by mid-century is correct, life in the decades ahead will likely become increasingly local and smaller in scale. These changes will create opportunities to produce foods locally in ways that nurture relationships among soil, water, plants, herbivores, farmers, ranchers, and consumers, who will all need to learn what it means to be locally adapted to our environments. Livestock can be our partners in fashioning diverse plant communities that create health for herbivores, omnivores, and carnivores below and above ground.

Introduction

The first paper in this series highlighted how the "taste of a place," or terroir, enables animals to nourish and self-medicate by learning to eat nutritious combinations of foods in utero and early in life, selecting phytochemically and biochemically rich foods from diverse foodscapes, and adapting food preferences as needs change via metabolically mediated flavor-feedback associations that link cells and organs with palates. The flexibility of these processes enables animals to transform epigenetically and behaviorally as environments change. For herbivorous livestock and omnivorous people, phytochemically and biochemically rich diets comprised of wholesome foods bolster health and protect against diseases (1).

Yet, during the past century industrial agriculture has emphasized yields over the phytochemical and biochemical richness of meat, dairy, and produce. As a result, meat, vegetables, and fruits look great on grocery store shelves, but they lack flavor, in no small part due to a lack of nutrient richness. At the same time, the food industry learned to make energy-rich ultra-processed foods exceedingly

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flavorful. Agricultural and food industries thus disincentivized "real" foods because they lack flavor, while making ultra-processed food irresistible.

That was not so during the previous 300,000 years *Homo sapiens* lived on Earth, when our ancestors hunted and gathered for nourishment. Only in the past 10,000 years did we transition from hunters and gatherers to pastoralists and small-scale farmers and ranchers. And only during the past century did we create civilizations dependent upon fossil fuels and industrial agriculture, a move some anthropologists claim is the worst mistake our species has ever made (2).

That "mistake" was exacerbated by the Green Revolution, as farming stressed the low diversity of high-yielding crops over the high diversity and nutritional quality of foods (1–3). We abandoned locally adapted species of plants and animals in favor of a few varieties and breeds. Conversely, our ancestors used hundreds of plants and animals for food, medicine, clothing, and shelter. We thus transformed from sunlight-driven ecological economies linked with Earth to money-centric economies disconnected from nature and dependent on fossil fuels (4, 5).

Our species is now grappling with warming climates and the ever-diminishing carrying capacity of a planet that no longer offers easily accessible and inexpensive fossil fuels (4, 5). Confronting these challenges will require changes in agriculture and food systems that bring us to the crux of another conundrum: How should people apportion scarce resources, and which foods should we grow for human consumption? To some, the answer is simple: allocate fewer resources such as water to growing food, stop growing crops for livestock, and transition to plant-based diets. Yet advocates of plant-based diets ignore key issues related to human fitness and planetary health.

Herbivores, Omnivores, Carnivores

The terrain that links human nutrition and health with planetary health is not easily traversed. People attempt to follow the advice of authorities, but experts seldom agree, and their advice changes constantly, often influenced by bias, arrogance, and corporate associations (1, 6). Issues of diet and health become religious convictions with iniquity, damnation, and salvation as common themes (1). As a case in point, the EAT-Lancet Commission Report, written by 37 scientists from 16 countries to recommend diets and food production practices worldwide, has created a modern holy war by advocating a mostly meatless diet (6,7). To cool a warming planet and enhance human health, these scientists assert that we must increase our intake of vegetables, fruits, nuts, and legumes and all but eliminate red meat from our diets (7–9). They maintain the benefits of a plant-based diet are better health, as eating animal products can cause diabetes, high blood pressure, heart disease, and certain cancers. Those sentiments helped to spawn alternative meat ventures that falsely claim faux meat is like real meat (10). Yet, rigorous research does not support eliminating or reducing the intake of red meat below recommended levels (11–14). Most humans are omnivorous because a mix of plant and animal foods can most efficiently and effectively meet our needs for required nutrients (15, 16).

In *The Great Plant-Based Con*, Jayne Buxton provides a comprehensive review of scientific literature revealing why eating a plant-only diet will not improve human health or save the planet (17). Her book is neither anti-plant nor anti-vegan. Rather, it is a call for us to assess facts about human diets and their environmental effects. She reveals how the efforts of a constellation of individuals, corporations, and organizations with vested interests in plant-based agriculture, foods, and meats are leading us down a path with severe repercussions for our health and wellbeing and that of the planet. She concludes removing animal foods from our diet is a serious threat to human and environmental health and a red herring regarding climate change.

Indeed, the EAT-Lancet guidelines are not feasible given the diverse ways people produce plant and animal foods in the environments they inhabit worldwide, they may exacerbate food inequity, and will likely increase mental illness (18–20). While plant-based diets are associated with better cognitive and affective outcomes than ultra-processed diets, those that severely limit animal products are not (21). Individuals who adhere to advice to severely limit intake of meat report poorer mood and are at risk of being deficient in nutrients, including bioavailable amino acids, selenium, zinc, iron, and vitamins B9 (folate) and B12 (cobalamin) (20, 21). Conversely, moderate meat consumption has been linked with lower rates of depression and anxiety, which reflects the amino acids and other nutrients meat provides (22–25). Taurine, for example, reduces cellular senescence, protects against telomerase deficiency, suppresses mitochondrial dysfunction, decreases DNA damage, and attenuates inflammation (23).

Certainly, plants are vitally important for human health. They more readily meet our needs for vitamin C and magnesium, and they are often higher than meats in folate, manganese, thiamin, potassium, vitamin E, and numerous health-promoting phytochemicals (15, 16). In addition to their many health-promoting properties, phytochemicals also antagonize the deleterious effects of compounds found in cooked red meat, including heterocyclic amines, nitroso compounds, malondialdehyde, and advanced glycation end products (15, 16). Such findings help explain why omnivorous diets rich in plants do not show links between red meat consumption and negative health outcomes often observed in population studies of people who consume the standard American/Western diet, which is high in ultra-processed foods and low in phytochemically rich plants (26). In addition, substituting just 10% of daily caloric intake from beef and processed meats with fruits, vegetables, nuts, legumes, and selected seafood can profoundly affect health while also reducing the carbon footprint of most Americans by nearly a third (27).

Relative to plants, meat provides the following nutrients in highly bioavailable forms: all the essential amino acids; minerals such as calcium, iron, selenium, and zinc; vitamins A (retinol), B12 (adenosyl- and hydroxocobalamin), D (cholecalciferol), and K2 (menaquinone-4); and long-chain polyunsaturated fatty acids including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which are most readily, or solely, obtained from meat (15, 16). Eating a small amount (30 g) of beef can meet the daily needs of a healthy 70-kg adult for taurine, carnosine, creatine, anserine, and 4-hydroxyproline, which improve metabolic, retinal, immunological, muscular, cartilage, neurological, and cardiovascular health (28). That is why a recent report by the Food and Agriculture Organization (FAO), based on over 500 scientific papers and 250 policy documents, concludes meat, eggs, and milk are essential sources of nutrients for human health (29). The report also emphasizes the need for sustainable livestock production practices to ensure the continued availability and accessibility of these nutrient-dense foods.

Importantly, an omnivorous diet with high nutrient richness and density can more efficiently meet nutritional needs (30–32). Requirements for all 9 essential amino acids can be met with a mix of plants, but meat, milk, or eggs contain all the essential amino acids, and they are better digested and assimilated than those in plants (33). Thus, a person can eat less animal than plant matter to meet needs. For example, assuming 113 grams of skinless chicken breast yields 31 grams of protein and 155 calories, to get the same amount of protein from plants, we must eat 1.5 cups of legumes, 1.5 cups of rice, and 1 cup of veggies, for a total of nearly 700 calories. Greater intake of less digestible plant diets increases human methane (flatulence), stool frequency, and stool weight (34). In other assessments of nutritional adequacy, plant-only diets resulted in more nutrient deficits, a greater excess of ingested calories, and a need to eat more foods (35).

The nutritional importance of meat helps to explain why, even though most vegetarians report a low desire to eat meat, their neural activity reveals a craving for meat (36). Their response highlights the discord between acquired beliefs—regarding, for example, animal welfare, human and environmental health—and the inherent need for nutrients in meat. That discord helps to explain why 86% of people who become vegetarians, and 70% of those who become vegans, revert to an omnivorous diet (37). In 2014, only 2% of Americans did not eat any animal products, and this number had not changed appreciably for 20 years (37). Elsewhere, less than 10% of any population follows a vegetarian diet, other than in India, which has the highest proportion of vegetarians (30%) of any country (38, 39). There has been only limited success encouraging people to eat plant-based diets in high-income countries, though some consumers now identify as flexitarians who occasionally consume meat (40).

Ironically, many people who want to avoid eating meat for environmental or ethical reasons still crave meat, and they attempt in vain to get it through plant-based "meats" that do not contain the essential nutrients provided by real meat and that are not necessarily better for health (10, 21, 36). In the SWAP-MEAT trial, healthy adults ate 2 or more servings of plant-based "meats" daily for 8 weeks followed by 2 or more servings of animal meats daily for 8 weeks (or vice versa). When scientists conducted a secondary analysis of that trial, they found only 4 out of 92 biomarkers of inflammation were reduced to statistical significance (41). As the researchers pointed out, they expected much greater improvements in inflammation from the plant-based meats, although the 8-week length of time may have been too short to achieve detectable changes.

The plant vs meat holy war heats up even more when it comes to cooling a warming planet. Some scientists claim plant-based diets, which also include faux meat made from pea protein (Beyond Meat™) or soy protein (Impossible Foods™), are less harmful to the planet than meat-based diets (7, 8). Yet, when their carbon footprints—expressed as land used to produce crops or animals and as greenhouse gas emissions (GHGE)—are calculated to consider the needs for protein and essential amino acids, animal foods are like most plant foods due to the better ability of animal protein to meet our needs for amino acids (42, 43). While animal cell-based meat (cultured meat) might better meet

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nutritional needs, the environmental impact of current cultured meat production is orders of magnitude higher than beef production when a highly refined growth medium is used to produce animal cell-based meat (44).

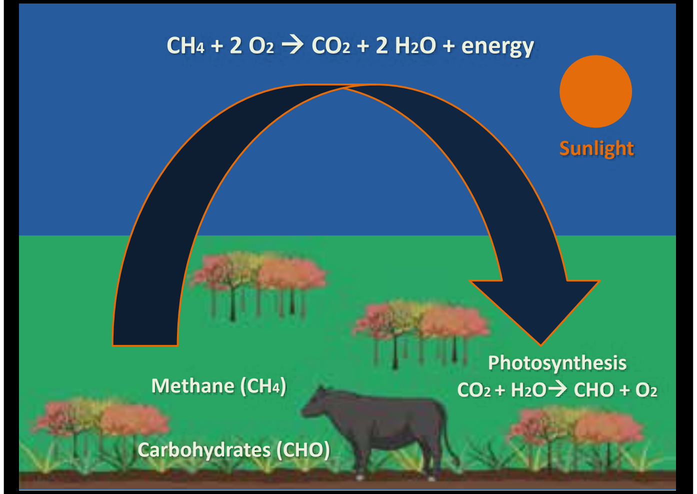
Others argue that pasture-fed beef and lamb are the world's most damaging food products due to the amount of land they require to produce food and the amount of methane they emit (45). They contend that, relative to plant foods, livestock need more land to produce a unit of food, so curbing meat in our diets would reduce the impacts of animal-based agriculture (7–9, 45). Certainly, livestock in feedlots compete with people for land to grow crops. Yet, when animals use grazing lands unsuitable for crops, they complement rather than compete with crops.

Scientists also disagree on the environmental impacts of fattening livestock on high-grain diets in feedlots as opposed to forage-based grazing systems. Some maintain feedlots have fewer impacts than grazing because, for land use and GHGE, feedlots generate fewer negative environmental effects per unit of meat produced (46). As they rightly point out, grazing systems that require high inputs of synthetic fertilizers, supplemental feed, or deforestation to create pastures have much greater climate impacts than feedlot systems. Yet, through managed grazing and by integrating livestock with farming, people need not rely on such GHGE-generating inputs (47).

If we transition to more pasture-based livestock production, some suggest we will have to reduce meat intake by nearly 40% due to the lack of land (48). Yet, well-managed grazing can increase the land's carrying capacity by 50–70% compared to unmanaged grazing of free-ranging animals, as can multi-species grazing with cattle, sheep, goats, and pigs (49, 50). With the advent of industrial agriculture, ruminants were removed from fertile lands now used to produce crops. The fertile prairies of the Midwest U.S., for example, were once a habitat for millions of wild and domestic herbivores and could still provide ample forage for grazing.

Regarding methane, of the estimated 737 million tons emitted globally each year, 50% comes from natural sources such as wildfires, wetlands, termites, oceans, and volcanos; 17% from fossil fuel production and use; 15% from livestock; 9% from landfills and waste; 4% from rice; and 4% from biofuel burning (51). Agriculture is the largest source of anthropogenic methane emissions, closely followed by the fossil-fuel industries' intentional release (gas venting) and unintentional leakage (fugitive emissions) of methane (52). However, methane from livestock and fossil fuels are distinctly different. Methane from livestock begins as carbon dioxide in the atmosphere, recycled by plants through photosynthesis (**Figure 1**). In contrast, methane from fossil fuels is newly added to the atmosphere from deep within the earth, where it has been for millions of years. The largest global cattle inventory was 1.101 billion in 1989, and cattle numbers have declined from 1989 to 2019 (53). Thus, most increases in methane emissions came from burning coal, oil, and natural gas for electricity and heat (31%) and transportation (15%) (51, 52).

Figure 1



Methane emissions from livestock

Use of fossil fuels accounts for 75% of all GHGE. Compared with pre-industrial levels, fossil fuel emissions increased atmospheric carbon dioxide by 50% and doubled methane (51, 52). Overall fossil-fuel emissions rose by 60% from 1991 to 2019, while agricultural emissions rose by only 16% (52). While a figure of 14.5% is typically used for GHGE from agriculture, that number varies for different parts of the world (25, 51). In the United Kingdom, cattle and sheep account for 3.7% of emissions, while cattle account for 35% in Latin America and the Caribbean. In the U.S., where global consumption of meat is the highest in the world, agriculture contributes 9% of emissions: 4% from animal agriculture and 5% from plant agriculture. A shift to a plant-based diet would mean growing far more crops, which could badly affect soil health and increase agricultural GHGE, given projected increases in soil erosion and GHGE from industrial farming where crops such as corn and soybeans are grown in vast monocultures (54).

Some people contend a plant-based diet orients the human spirit toward compassion by valuing the sentient lives of livestock. While eating a plant-based diet does not directly involve killing animals, indirectly it does. Crops are grown in monocultures where life below and above ground is destroyed by tillage, pesticides, and fertilizers (55). Though not alone, a striking example is grassland birds, whose numbers declined by over 50% in the last 50 years due to agriculture (56, 57). Even the most varied small vegetable farms are ecologically barren compared with diverse pastures and rangelands. Thus, the statement "nothing had to die so I can live" is based on ignorance of the millions of animals that died via loss of habitat to make a vegetable farm.

To further complicate these matters, scientists are coming to appreciate that plants and animals alike are conscious, and certainly for animals—and likely for plants—they are also sentient. Plant physiologists and molecular biologists are presenting compelling evidence that plants possess states of perception and awareness gained through as many as 20 senses (58–60). Learning and memory are vital as roots, stems, leaves, and flowers address environmental challenges. If we consider consciousness and sentience as part of awareness and perception, some argue plants are both conscious and sentient (61, 62). We should thus see all life as sacred and eating as an act that links us with plants and animals in endless transformation (1, 63).

Ultimately, the human diet is not as simple as a holy war of plant vs meat eaters. Given the diversity of cultures and environments where people live, one-size-fits-all policies for diets are bound to fail. To further confound the issue, no two individuals are alike in form or function (1). Hence, the mix of plant and animal foods that will work best will vary as a function of how each person is built and how their body functions. We must appreciate the many ways people nourish themselves globally and consider how we might sustain life on a warming planet. These multifaceted issues are the subject of a special issue of *Animal Frontiers* that discusses the roles of animals in human societies and provides an in-depth review of the science related to livestock and human health, livestock and the environment, and livestock and socioeconomics (64).

Chefs, Diets, and Ecological Doctors

Given the value of meat and dairy for human health, the question arises: How can we create partnerships with livestock that enhance the wellbeing of animals and humans while mitigating warming climates? While grazing by wild and domestic herbivores can adversely influence plant diversity, soil health, water quality, GHGE, and the health of people, well-managed grazing can have the opposite effects (65–69). In the U.S. we have come to rely on fences and grazing systems to positively influence the foraging behavior of livestock and the health of soil and plants, herbivores, and people. Compared with "hi-tech" tools and techniques in livestock husbandry and land management, the practices of shepherds seem a separate, archaic, folk world.

Yet, at the highest level of sophistication, a skilled shepherd is a "chef" who designs meal courses to improve ecosystem health in partnership with livestock including, but not limited to, goats, sheep, or cattle (70, 71) (**Figure 2**). A flock in the hands of an "ecological doctor" can enhance biodiversity, mitigate fires, sustain cultures, and reduce GHGE—benefits not considered in life cycle analyses. Those benefits matter given that two-thirds of the Earth's land mass, unsuitable for producing crops, is home to 2 billion pastoralists who depend on livestock for their livelihood, as do many people in the Americas, Europe, Turkey, the Middle East, Asia, and Africa who benefit from transhumant meat and dairy production (72, 73). The meat, dairy, wool, and leather provided by livestock are integrated into global markets for the other 6 billion people. As Ilse Köhler-Rollefson points out in *Hoofprints on the Land*, pastoralists amplify the economic and social benefits of livestock production while boosting the quantity and quality of the foods they produce through low-cost, non-fossil-fuel–based practices that include managed grazing, raising locally adapted animals, and eating high-quality meat and dairy products (72).

In addition to these benefits, pastoralists also mitigate human-wildlife conflicts. For example, Maasai in the Amboseli region of Kenya earn livestock-based livelihoods in challenging environments that include lion depredation on livestock (74). Pastoralism is essential to social-ecological resilience that includes retaining communal land tenure and cultural practices that support diverse wildlife populations, including large carnivores such as the African lion. Herding in ways that prevent carnivore-livestock conflicts supports the vitality of pastures as well as that of lions, ecosystems, and Maasai culture. Sadly, livestock losses have increased in recent years as more children attend school and adults devote less time to mentoring and herding.

Shepherds work in partnership with livestock, learning how to best move animals in ways that stimulate appetite and improve nutrition, health, welfare, and production (70, 71). Neither fences nor GPS shock collars can do what a knowledgeable herder can do to optimize grazing from diverse forage resources. By designing daily grazing circuits, a skilled shepherd can encourage the flock to use different forages from a mix of plants, some highly palatable and others less so. Indeed, the highest level of targeted grazing can be achieved through the relationship between a herder, a flock, and a landscape of plants considered weedy or

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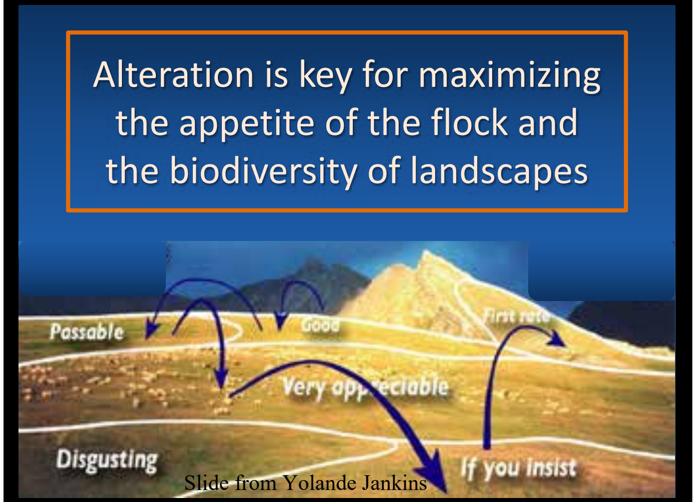
undesirable. Rather than attempt to eradicate these plant species with costly herbicides, which we will never do, we must learn how to use them through partnerships between shepherds and livestock (70, 71). Most weeds are highly nutritious, and in many cases, though not all, animals avoid them not because they are toxic but because they never learned how to eat them (1).

When researchers in France began to study livestock nutrition, they were astonished to see the levels of production that skilled shepherds obtained from animals foraging on rangelands. They came to realize these "chefs" were using an empirical understanding of complementarities among forage diversity to stimulate food intake and more fully utilize the range of plants available (70, 71). To do so, they design daily circuits to stimulate and satisfy an animal's appetite for different nutrients, regulate the intake of secondary compounds, and enhance the use of all the forages in an area (**Figure 2**). Meals include a moderation phase, which provides animals access to plants that are abundant but not highly preferred to calm a hungry flock; a main course with plants of moderate abundance and preference; a booster phase of highly preferred plants; and finally, a dessert phase of palatable plants that complement other forages.

Figure 2


Alteration is key for maximizing the appetite of the flock and the biodiversity of landscapes

Slide from Yolande Jankins

Managed grazing by a skilled pastoralist (Image courtesy of Yolande Jankins)

These findings raise intriguing questions about the degree to which wild and domesticated animals learn about complementarities and sequences as they forage across landscapes. Sheep on pastures with crested wheatgrass and 6 shrubs (sagebrush, rabbitbrush, winterfat, bitterbrush, kochia, fourwing saltbrush) established grazing

circuits with 3 phases to meals. They began each day with a meal of sagebrush, fed on grass and other shrubs at midday, and finished with a meal of fourwing saltbrush. Sheep offered shrubs had diets higher in energy and protein than sheep offered only crested wheatgrass during these winter-grazing studies (75).

Complementarities among secondary compounds enable herbivores to meet needs for nutrients and health-promoting phytochemicals while not swamping the same detoxification pathways in the rumen and the liver (1, 76). When lambs can choose between foods with nitrates or oxalates, they eat more than lambs offered food with only one of these phytochemicals (77). That is also true within the same class of secondary compounds because specific compounds—within general classifications such as alkaloids, tannins, and terpenes—differ in their structures and how they are detoxified. For example, mule deer eat more when offered sagebrush and juniper (12.3 g/kg body weight [BW]), plants with different kinds of terpenes, than when they are provided only sagebrush (4.2 g/kg BW) or juniper (7.8 g/kg BW) (78). Different kinds of tannins also complement one another and improve the health and performance of livestock (79).

Complementarities among secondary compounds are illustrated experimentally with sheep on pastures. When sheep are given a capsule of alkaloids just before they forage on pastures, they eat less tall fescue (high in alkaloids) and more birdsfoot trefoil and alfalfa (80). When given tannins, they eat less trefoil (high in tannins) and more fescue and alfalfa. Finally, when sheep are given saponins, they eat less alfalfa (high in saponins) and more trefoil and fescue.

Herbivores can better meet nutrient needs and reduce internal parasites when offered a mix of plants. For example, goats and sheep in Mediterranean scrublands eat *Pistacia lentiscus*, high in tannins, which adversely affects nematode fertility and prevents infestation with eggs. However, fecal egg excretion by nematodes is only partially impaired by tannins—terpenes in *P. lentiscus* act in synergy with tannins to further impede the survival of worms (81).

While complementarities among multiple secondary compounds are an important but little-understood area of plant-herbivore interactions, even less is known about how sequences of eating plants with different compounds affect foraging, though they appear important. For example, sheep eat much more food with terpenes when they first eat food with tannins, evidently because tannins bind with terpenes, mitigating their adverse effects (82). These findings are consistent with landscape-level studies that show ewes with a high preference for sagebrush, a shrub high in terpenes, also eat more bitterbrush, a shrub high in tannins, compared with ewes with a lower preference for sagebrush (83). Cattle eat very little endophyte-infected tall fescue when they first graze tall fescue alone for 30 minutes, followed by trefoil, alfalfa, or alfalfa-trefoil combination for 60 minutes (84). Conversely, when the sequence is reversed, cattle forage actively on trefoil, alfalfa, or trefoil-alfalfa combination and then feed actively on fescue during a 90-minute meal. These patterns of foraging are similar for sheep (85).

Like shepherds, some "human herders" take advantage of interactions among plants to promote health and prevent toxicosis in people, as exemplified by various herb combinations used in Chinese medicine (86). Herbalists classify outcomes of interactions as *reinforcement* when herbs have similar properties which together produce a greater effect; as *potentiation* when herbs have different properties, and one helps strengthen the properties of the other; and as *restraint/detoxification* when herbs have different properties with one herb detoxifying or nullifying the negative side effects of the primary acting herb. As discussed in the first paper in this series, relationships among phytochemical diversity and animal health can also positively influence the quality of meat and dairy for human health (15, 16, 87). Indeed, plant diversity creates health for herbivores, omnivores, and carnivores below and above ground, and livestock can be our partners in fashioning diverse plant communities that enable One Health.

Human Diets, Fossil Fuels, and Changing Climates

Like skilled herders and their flocks, we can link our palates with foodscapes to reduce GHGE while creating human and environmental health. When a projected population increase to 10 billion people by 2050 is combined with a 32% increase in per-person emissions from global shifts to ultra-processed diets, the net effect is an 80% increase in GHGE from food production and consumption (88). Studies in Japan and Australia support the claim that ultra-processed foods are major contributors to GHGE (89, 90). Alternatively, diets of wholesome foods—meat, dairy, eggs, fruits, vegetables, and grains—would not increase GHGE (88).

The global shift from eating nutrient-rich whole foods to ultra-processed foods high in refined carbohydrates has encouraged 2.1 billion people to overeat and become overweight or obese. This change was illustrated in a study where people ate either ultra-processed or wholesome foods matched for energy, protein, sugar, fat, sodium,

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and fiber (30). People fed the ultra-processed diet, which included white bread, sugary cereals, and reconstituted meats, ate an extra 500 calories daily compared to those offered wholesome foods, including unprocessed meat, fresh fruits and vegetables, and whole grains. People who ate ultra-processed foods gained significantly more weight during the 2-week trial. Compared with whole plant and animal foods, ultra-processed foods do little to induce satiation, the physical and biochemical processes that bring a meal to an end, or satiety, the processes that inhibit eating between meals.

Steadily embedding ultra-processed foods in our diets has been an experiment of sorts (91, 92). Replicate the study over generations—in the womb, childhood, teen, and adult years—and we now have an epidemic of diet-related diseases (21, 93, 94). Given these trends, it is foolish to think introducing more ultra-processed foods—including plant-based meat alternatives— into our diet will reverse the burden of diet-related diseases (21). Indeed, our experiences of the recent past provide a good idea of the likely outcome: a continued rise in diet-related diseases.

Another basic issue is lurking within the confines of industrial agriculture, ultra-processed foods, human health, and GHGE. To produce a single calorie of food, industrial agriculture requires a minimum of 2 calories of fossil fuels for machinery to plant, irrigate, and harvest crops and for fertilizers, herbicides, and insecticides to grow and protect plants in monocultures (1, 4). We use another 8-12 calories of fossil fuels to process, package, deliver, store, and cook food. No organism can survive while expending far more energy than it consumes. And neither can we.

Since the 1900s, fossil fuels have become the source of oil that runs the machines that till, seed, harvest, and transport crops in industrial agriculture. The fossil fuel-intensive Haber-Bosch process, developed in the early 1900s by Fritz Haber and later modified for commercial production by Carl Bosch, uses natural gas to turn atmospheric nitrogen into ammonia to make nitrogen fertilizers used by industrial agriculture to grow crops without manure from livestock. Prior to fossil fuels, livestock helped till, seed, harvest, and transport crops. They also provided the manure farmers used to naturally fertilize their fields. Now, farmers "fertilize" the air and land with GHGE and other pollutants produced by fossil-fuel-burning tractors.
It is easy to understand why we embraced fossil fuels. The energy in a barrel of oil is equivalent to 3 to 12 years of work by a fit human, depending on the task (95). Fossil fuels transformed agriculture from long days of hard work into an industry where fertilizers, herbicides, pesticides, and machines do the work. Ironically, the founder of the Green Revolution, Norman Borlaug, intended to feed hungry people and decrease population growth. He did not foresee that industrial agriculture would help humans exceed the carrying capacity of the planet as our population soared from 2 million people in 10,000 BCE, to nearly a billion in 1800, to 8 billion people today. Nor did he expect the Green Revolution to contribute to the sixth mass extinction (56). The ecological, economic, and social costs of our dependence on fossil fuels have become unsustainable (5). Oddly, economic models, built upon land, labor, and capital, do not reflect the singular importance of formerly inexpensive energy derived from fossil fuels (5).

Each day in 2021, the US population of nearly 330 million used over 18.7 million barrels of oil, the United Kingdom population of over 67 million used over 1.24 million barrels a day, and globally we used over 97 million barrels of oil. Estimates of remaining oil and natural gas stocks vary, but inexpensive high-quality oil has been found and exploited (5, 96–98). Some groups project oil and natural gas will run out by mid-century (99–102). Which peoples will need to change most from lack of fossil fuels: pastoralists still largely sustained by solar economies or people in nations built upon and now largely reliant upon fossils to fuel their economies (72)? In the final paper of this series, I explore some ways to become locally adapted to the environments we inhabit and to learn once again to nurture one another and the communities we inhabit.

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References

1. Provenza FD. *Nourishment: What Animals Can Teach Us About Rediscovering Our Nutritional Wisdom*. Chelsea Green; 2018.

2. Diamond J. *Guns, Germs, and Steel: The Fates of Human Societies*. W.W. Norton & Company; 1999.

3. Provenza FD, Villalba JJ, Haskell JH, et al. The value to herbivores of plant physical and chemical diversity in time and space. *Crop Sci.* 2007;47(1): 382-398. https://doi.org/10.2135/cropsci2006.02.0083

4. Jackson W, Jensen R. Let's get 'creaturely': a new worldview can help us face ecological crises. https://tinyurl.com/getcreaturely

5. Hagens NJ. Economics for the future — beyond the superorganism. *Ecol Econ*. 2020;169:106520. https://doi.org/10.1016/j.ecolecon.2019.106520

6. Rubin R. Backlash over meat dietary recommendations raises questions about corporate ties to nutrition scientists. *J Am Med Assoc*. 2020; 323(5):401-404. https://doi.org/10.1001/jama.2019.21441

7. Willett W, Rockström J, Loken B, et al. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet*. 2019;393(10170):447-492. https://doi.org/10.1016/S0140-6736(18)31788-4

8. Project Drawdown. *Farming our way out of the climate crisis*. 2020; https://tinyurl.com/drawdownag.

9. Godfray HCJ, Aveyard P, Garnett T, et al. Meat consumption, health, and the environment. *Science*. 2018;361(6399):eaam5324. https://doi.org/10.1126/science.aam5324

10. van Vliet S, Bain JR, Muehlbauer MJ, et al. A metabolomics comparison of plant-based meat and grass-fed meat indicates large nutritional differences despite comparable Nutrition Facts panels. *Sci Reports*. 2021b;11: 13828. https://doi.org/10.1038/s41598-021-93100-3

11. Zeraatkar D, Han MA, Guyatt GH, et al. Red and processed meat consumption and risk for all-cause mortality and cardiometabolic outcomes: a systematic review and meta-analysis of cohort studies. *Ann Intern Med*. 2019;171:703-710. https://doi.org/10.7326/M19-0655

12. Vernooij RWM, Zeraatkar D, Han MA, et al. Patterns of red and processed meat consumption and risk for cardiometabolic and cancer outcomes: a systematic review and meta-analysis of cohort studies. *Ann Intern Med*. 2019;171(10):732-741. https://doi.org/10.7326/M19-1583

13. Zagmutt FJ, Pouzou JG, Costard S. The EAT-Lancet commission's dietary composition may not prevent noncommunicable disease mortality. *J Nutr*. 2020;150(5):985-988. https://doi.org/10.1093/jn/nxaa020

14. Nordhagen S, Beal T, Haddad L. The role of animal-source foods in healthy, sustainable, and equitable food systems. *Global Alliance for Improved Nutrition* (GAIN). Discussion paper series #5. 2020. https://doi.org/10.36072/dp.5

15. van Vliet S, Provenza FD, Kronberg SL. Health-promoting phytonutrients are higher in grass-fed meat and milk. *Front Sustain Food Syst*. 2021a; 4:555426. https://doi.org/10.3389/fsufs.2020.555426

16. van Vliet S, Kronberg SL, Provenza FD. Plant-based meats, human health, and climate change. *Front Sustain Food Syst*. 2020;4:128. https://doi.org/10.3389/fsufs.2020.00128

17. Buxton J. *The Great Plant-Based Con: Why Eating a Plants-Only Diet Won't Improve Your Health or Save the Planet*. Piatkus; 2022.

18. Hirvonen K, Bai Y, Headey D, Masters WA. Affordability of the EAT-Lancet reference diet: a global analysis. *Lancet Glob Health*. 2020;8, e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4

19. Wang VH, Foster V, Yi SS. Are recommended dietary patterns equitable? *Public Health Nutr*. 2022;25(2):464–470. https://doi.org/10.1017/S1368980021004158

20. Young HA. Adherence to the EAT-Lancet diet: unintended consequences for the brain? *Nutrients* 2022;14(20):20. https://doi.org/10.3390/nu14204254

21. Prescott SL, D'Adamo CR, Holton KF, Ortiz S, Overby N, Logan AC. Beyond plants: the ultra-processing of global diets is harming the health of people, places, and planet. *Int J Environ Res Public Health* 2023;20(15):6461. https://doi.org/10.3390/ijerph20156461

22. Beal T, Ortenzi F. Priority micronutrient density in foods. *Front Nutr*. 2022;9:806566. https://doi.org/10.3389/fnut.2022.806566

23. Singh P, Gollapalli K, Mangiola S, et al. Taurine deficiency as a driver of aging. *Science*. 2023;380(6649):eabn9257. https://doi.org/10.1126/science.abn9257

24. Dobersek U, Teel K, Altmeyer S, Adkins J, Wy G, Peak J. Meat and mental health: a meta-analysis of meat consumption, depression, and anxiety. *Crit Rev Food Sci Nutr*. 2023;63(19):3556-3573. https://doi.org/10.1080/10408398.2021.1974336

25. Marche C, Poulain M, Nieddu A, Errigo A, Dore MP, Pes GM. Is a plant-based diet effective to maintain a good psycho-affective status in old age? Results of a survey of a long-lived population from Sardinia. *Nutr Neurosci*. 2023;2023:1-10. https://doi.org/10.1080/1028415X.2023.2198115

26. Kappeler R, Eichholzer M, Rohrmann S. Meat consumption and diet quality and mortality in NHANES III. *Eur J Clin Nutr*. 2013;67:598-606. https://doi.org/10.1038/ejcn.2013.59

27. Stylianou KS, Fulgoni VL III, Jolliet O. Small targeted dietary changes can yield substantial gains for human health and the environment. *Nat Food*. 2021;2(8):616-627. https://doi.org/10.1038/s43016-021-00343-4

28. Wu G. Important roles of dietary taurine, creatine, carnosine, anserine and 4-hydroxyproline in human nutrition and health. *Amino Acids*. 2020;52(3):329-360. https://doi.org/10.1007/s00726-020-02823-6

29. Food and Agriculture Organization of the United Nations. *Contribution of terrestrial animal source food to healthy diets for improved nutrition and health outcomes*. FAO; 2023. https://tinyurl.com/fao3912

30. Hall KD, Ayuketah A, Brychta R, et al. Ultra-processed diets cause excess calorie intake and weight gain: an inpatient randomized controlled trial of ad libitum food intake. *Cell Metab*. 2019;30(1):67-77.e3. https://doi.org/10.1016/j.cmet.2019.05.008

31. Montgomery DR, Biklé A, Archuleta R, Brown P, Jordan J. Soil health and nutrient density: preliminary comparison of regenerative and conventional farming. *PeerJ*. 2022;10:e12848. https://doi.org/10.7717/peerj.12848

32. Lonnie M, Hooker E, Brunstrom JM, et al. Protein for life: review of optimal protein intake, sustainable dietary sources and the effect on appetite in ageing adults. *Nutrients*. 2018;10(3):360. https://doi.org/10.3390/nu10030360

33. Boye J, Wijesinha-Bettoni R, Burlingame B. Protein quality evaluation twenty years after the introduction of the protein digestibility corrected amino acid score method. *Br J Nutr*. 2012;108(suppl 2):S183-S211. https://doi.org/10.1017/S0007114512002309

34. Barber C, Mego M, Sabater C, et al. Differential effects of Western and Mediterranean-type diets on gut microbiota: a metagenomics and metabolomics approach. *Nutrients*. 2021;13(8):2638. https://doi.org/10.3390/nu13082638

35. White RR, Hall MB. Nutritional and greenhouse gas impacts of removing animals from US agriculture. *Proc Natl Acad Sci USA*. 2017;114(48):E10301-E10308. https://doi.org/10.1073/pnas.1707322114

ISSN 2474-1906

36. Giraldo M, Buodo G, Sarlo M. Food processing and emotion regulation in vegetarians and omnivores: an event-related potential investigation. *Appetite*. 2019;141:104334. https://doi.org/10.1016/j.appet.2019.104334

37. Herzog H. 84% of vegetarians and vegans return to meat. Why? *Psychology Today*. 2014. https://tinyurl.com/psychveg

38. Szenderák J, Fróna D, Rákos M. Consumer acceptance of plant-based meat substitutes: a narrative review. *Foods*. 2022;11(9):1274. https://doi.org/10.3390/foods11091274

39. Appleby PN, Key TJ. The long-term health of vegetarians and vegans. *Proc Nutr Soc*. 2016;75(3):287–293. https://doi.org/10.1017/S0029665115004334

40. Dagevos, H. Finding flexitarians: current studies on meat eaters and meat reducers. *Trends Food Sci Technol*. 2021;114:530-539. https://doi.org/10.1016/j.tifs.2021.06.021

41. Crimarco A, Landry MJ, Carter MM, Gardner CD. Assessing the effects of alternative plant-based meats v. animal meats on biomarkers of inflammation: a secondary analysis of the SWAP-MEAT randomized crossover trial. *J Nutr Sci*. 2022;11:e82. https://doi.org/10.1017/jns.2022.84

42. Tessari P, Lante A, Mosca G. Essential amino acids: master regulators of nutrition and environmental footprint? *Sci Reports*. 2016;6:26074. https://doi.org/10.1038/srep26074

43. McAuliffe GA, Takahashi T, Beal T, et al. Protein quality as a complementary functional unit in life cycle assessment (LCA). *Int J Life Cycle Assess*. 2023;28(2):146-155. https://doi.org/10.1007/s11367-022-02123-z

44. Risner D, Kim Y, Nguyen C, Siegel JB, Spang ES. Environmental impacts of cultured meat: a cradle-to-gate life cycle assessment. *bioRxiv*. 2023. https://doi.org/10.1101/2023.04.21.537778

45. Monbiot G. *Regenesis: Feeding the World Without Devouring the Planet.* Penguin Press; 2022.

46. Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. *Science*. 2018;360:987–992. https://doi.org/10.1126/science.aaq0216

47. Provenza FD, Kronberg SL, Gregorini P. Is grassfed meat and dairy better for human and environmental health? *Front Nutr*. 2019;6:26. https://doi.org/10.3389/fnut.2019.00026

48. Hayek MN, Garrett RD. Nationwide shift to grassfed beef requires larger cattle population. *Environ Res Lett*. 2018;13(8):084005. https://doi.org/10.1088/1748-9326/aad401

49. Teague R, Kreuter U. Managing grazing to restore soil health, ecosystem function, and ecosystem services. *Front Sustain Food Syst.* 2020;4:534187. https://doi.org/10.3389/fsufs.2020.534187

50. Martin G, Barth K, Benoit M, et al. Potential of multi-species livestock farming to improve the sustainability of livestock farms: a review. *Agric Syst*. 2020;181:102821. https://doi.org/10.1016/j.agsy.2020.102821

51. Environmental Protection Agency. *Global greenhouse gas emissions data*. EPA; 2022. https://tinyurl.com/ghgemit.

52. Liu S, Proudman J, Mitloehner FM. Rethinking methane from animal agriculture. *CABI Agric Biosci*. 2021;2(1):22. https://doi.org/10.1186/s43170-021-00041-y

53. Cook R. *World cattle inventory by year*. Beef2Live; 2023. https://tinyurl.com/cattleinv. Accessed April 26, 2023.

54. O'Neal MR, Nearing MA, Vining RC, Southworth J, Pfeifer RA. Climate change impacts on soil erosion in Midwest United States with changes in crop management. *Catena*. 2005;61(2-3):165-184. https://doi.org/10.1016/j.catena.2005.03.003

55. Fischer B, Lamey A. Field deaths in plant agriculture. *J Agric Environ Ethics*. 2018;31(4):409-428. https://doi.org/10.1007/s10806-018-9733-8

56. Kolbert E. *The Sixth Extinction: An Unnatural History*. Henry Holt and Company; 2014.

57. Rosenberg KV, Dokter AM, Blancher PJ, et al. Decline of the North American avifauna. *Science*. 2019;366(6461):120-124. https://doi.org/10.1126/science.aaw1313

58. Chamovitz D. *What a Plant Knows: A Field Guide to the Senses*. Scientific American/Farrar, Straus and Giroux; 2012.

59. Trewavas A. *Plant behaviour & intelligence*. Oxford University Press; 2014. https://doi.org/10.1093/acprof:oso/9780199539543.001.0001

60. Mandelbaum R. Plant intelligence: recent research findings and their implications. *J Am Holist Vet Med Assoc*. 2019;54:28-35.

61. Mancuso S. *The Revolutionary Genius of Plants: a New Understanding of Plant Intelligence and Behavior*. Simon & Schuster; 2018.

62. Segundo-Ortin M, Calvo P. Plant sentience? Between romanticism and denial: science. *Animal Sentience*. 2023;33(1). https://doi.org/10.51291/2377-7478.1772

63. Provenza FD, Anderson C, Gregorini P. We are the earth and the earth is us: how palates link foodscapes, landscapes, heartscapes, and thought scapes. *Front Sustain Food Syst*. 2021;5:547822. https://doi.org/10.3389/fsufs.2021.547822

64. Ederer P, Leroy F. The societal role of meat—what the science says. *Anim Front*. 2023;13(2):3-8. https://doi.org/10.1093/af/vfac098

65. Kauffman JB, Beschta RL, Lacy PM, Liverman M. Livestock use on public lands in the Western USA exacerbates climate change: implications for climate change mitigation and adaptation. *Environ Manage*. 2022;69(6):1137-1152. https://doi.org/10.1007/s00267-022-01633-8

66. Kauffman JB, Cummings DL, Kauffman C, et al. Bison influences on composition and diversity of riparian plant communities in Yellowstone National Park. *Ecosphere*. 2023;14(2). https://doi.org/10.1002/ecs2.4406

67. Teague WR, Apfelbaum S, Lal R, et al. The role of ruminants in reducing agriculture's carbon footprint in North America. *J Soil Water Conserv*. 2016;71(2):156-164. https://doi.org/10.2489/jswc.71.2.156

68. Intergovernmental Panel on Climate Change. *Special report: global warming of 1.5 °C*. IPPC; 2019. https://www.ipcc.ch/sr15/

69. Thompson LR, Rowntree JE. Invited Review: methane sources, quantification, and mitigation in grazing beef systems. *Appl Anim Sci*. 2020;36(4):556-573. https://doi.org/10.15232/aas.2019-01951

70. Meuret M, Provenza FD. When art and science meet: integrating knowledge of French herders with science of foraging behavior. *Rangeland Ecol Manag*. 2015;68(1):1-17. https://doi.org/10.1016/j.rama.2014.12.007

71. Meuret M, Provenza FD. How French shepherds create meal sequences to stimulate intake and optimise use of forage diversity on rangeland. *Anim Prod Sci*. 2015;55(3):309-318. https://doi.org/10.1071/AN14415

ISSN 2474-1906

72. Köhler-Rollefson I. *Hoofprints on the Land: How Traditional Herding and Grazing Can Restore the Soil and Bring Animal Agriculture Back in Balance With the Earth*. Chelsea Green; 2023.

73. Varijakshapanicker P, Mckune S, Miller L, et al. Sustainable livestock systems to improve human health, nutrition, and economic status. *Anim Front*. 2019;9(4):39-50. https://doi.org/10.1093/af/vfz041

74. Jablonski KE, Merishi J, Dolrenry S, Hazzah L. Ecological doctors in Maasailand: identifying herding best practices to improve livestock management and reduce carnivore conflict. *Front Sustain Food Syst*. 2020;4:118. https://doi.org/10.3389/fsufs.2020.00118

75. Gade AE, Provenza FD. Nutrition of sheep grazing crested wheatgrass versus crested wheatgrass-shrub pastures during winter. *J Range Manage*. 1986;39(6):527-530. https://doi.org/10.2307/3898764

76. Provenza FD, Villalba JJ, Dziba LE, Atwood SB, Banner RE. Linking herbivore experience, varied diets, and plant biochemical diversity. *Small Rumin Res*. 2003;49(3):257-274. https://doi.org/10.1016/S0921-4488(03)00143-3

77. Burritt EA, Provenza FD. Role of toxins in intake of varied diets by sheep. *J Chem Ecol*. 2000;26(8):1991-2005. https://doi.org/10.1023/A:1005565228064

78. Smith AD. Adequacy of some important browse species in overwintering mule deer. *J Range Manage*. 1959;12(1):9-13. https://doi.org/10.2307/3895208

79. Villalba JJ, Beauchemin KA, Gregorini P, MacAdam JW. Pasture chemoscapes and their ecological services. *Transl Anim Sci*. 2019;3(2):829-841. https://doi.org/10.1093/tas/txz003

80. Villalba JJ, Provenza FD, Clemensen AK, Larsen R, Juhnke J. Preference for diverse pastures by sheep in response to intraruminal administrations of tannins, saponins, and alkaloids. *Grass Forage Sci*. 2011;66(2):224-236. https://doi.org/10.1111/j.1365-2494.2010.00779.x

81. Landau S, Azaizeh H, Muklada H, et al. Anthelmintic activity of *Pistacia lentiscus* foliage in two Middle Eastern breeds of goats differing in their propensity to consume tannin-rich browse. *Vet Parasitol*. 2010;173(3-4):280-286. https://doi.org/10.1016/j.vetpar.2010.07.006

82. Mote T, Villalba JJ, Provenza FD. Foraging sequence influences the ability of lambs to consume foods containing tannins and terpenes. *Appl Anim Behav Sci*. 2008;113:57-68. https://doi.org/10.1016/j.applanim.2007.10.003

83. Seefeldt SS. Consequences of selecting Ramboulliet ewes for Mountain Big Sagebrush (*Artemisia tridentata* ssp. *vaseyana*) dietary preference. *Rangeland Ecol Manage*. 2005;58(4):380-384. https://doi.org/10.2111/1551-5028(2005)058[0380:COSREF]2.0.CO;2

84. Lyman TD, Provenza FD, Villalba JJ, Wiedmeier RD. Cattle preferences differ when endophyte-infected tall fescue, birdsfoot trefoil, and alfalfa are grazed in different sequences. *J Anim Sci*. 2011;89(4):1131-1137. https://doi.org/10.2527/jas.2009-2741

85. Lyman TD, Provenza FD, Villalba JJ. Influence of diet sequence on intake of foods containing ergotamine D tartrate, tannins and saponins by sheep. A*ppl Anim Behav Sci*. 2013;144(1-2):57-62. https://doi.org/10.1016/j.applanim.2012.12.006

86. Che C-T, Wang ZJ, Chow MSS, Lam CWK. Herb-herb combination for therapeutic enhancement and advancement: theory, practice and future perspectives. *Molecules*. 2013;18(5):5125-5141. https://doi.org/10.3390/molecules18055125

87. Zanon T, Komainda M, Ammer S, Isselstein J, Gauly M. Diverse feed, diverse benefits — the multiple roles of feed diversity at pasture on ruminant livestock production — a review. *J Vet Sci Anim Husb*. 2022;10(1):101. https://tinyurl.com/diversefeed

88. Tilman D, Clark M. Global diets link environmental sustainability and human health. *Nature*. 2014;515:518-522. https://doi.org/10.1038/nature13959

89. Kanemoto K, Moran D, Shigetomi Y, Reynolds C, Kondo Y. Meat consumption does not explain differences in household food carbon footprints in Japan. *One Earth*. 2019;1(4):464-471. https://doi.org/10.1016/j.oneear.2019.12.004

90. Ridoutt B, Anastasiou K, Baird D, Garcia JN, Hendrie G. Cropland footprints of Australian dietary choices. *Nutrients*. 2020;12(5):1212. https://doi.org/10.3390/nu12051212

91. Schatzker M. *The Dorito effect: The surprising new truth about food and flavor*. Simon & Schuster; 2015.

92. Scrinis G. Ultra-processed foods and the corporate capture of nutrition—an essay by Gyorgy Scrinis. *BMJ*. 2020;371:m4601. https://doi.org/10.1136/bmj.m4601

93. Mennella JA. Ontogeny of taste preferences: basic biology and implications for health. *Am J Clin Nutr*. 2014;99:704S-711S. https://doi.org/10.3945/ajcn.113.067694

94. Costa CS, Del-Ponte B, Assunção MCF, Santos IS. Consumption of ultra-processed foods and body fat during childhood and adolescence: a systematic review. *Public Health Nutr*. 2018;21(1):148-159. https://doi.org/10.1017/S1368980017001331

95. FatCatWatch. A barrel of crude oil is worth $164,000 — the human labor equivalent of a barrel of oil. FatCatWatch; 2011. Accessed June 26, 2023. https://tinyurl.com/crude-barrel

96. Mohr S, Wang J, Ellem G, et al. Projection of world fossil fuels by country. *Fuel*. 2015;141:120-135. https://doi.org/10.1016/j.fuel.2014.10.030

97. Fustier K, Gray G, Gunderson C. Hilboldt T, Global oil supply. Will mature field declines drive next supply crunch? HSBC Global Research; 2016. Accessed June 26, 2023. https://tinyurl.com/mature-field

98. Masnadi M, Brandt A. Energetic productivity dynamics of global super-giant oilfields. *Energy Environ Sci*. 2017;10:1493-1504. https://doi.org/10.1039/C7EE01031A

99. Shafiee S, Topal E. When will fossil fuel reserves be diminished? *Energy Policy*. 2009;37:181-189. https://doi.org/10.1016/j.enpol.2008.08.016

100. Kuo G. When fossil fuels run out, what then? Millennium Alliance for Humanity and the Biosphere; 2019. Accessed June 26, 2023. https://tinyurl.com/fossil-run

101. MET Group. When will fossil fuels run out? MET Group; 2021. https://tinyurl.com/fuel-run. Accessed June 26, 2023.

102. International Energy Agency. *World energy outlook 2022*. IEA; 2022. https://tinyurl.com/weo22. Accessed June 26, 2023.

ISSN 2474-1906