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Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins

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Abstract

Dietary transitions have resulted in generally higher meat intakes. Intensive feeding of animals is a rather inefficient way of producing dietary protein and it has also a variety of undesirable environmental and health impacts. Partial substitution of meat protein by plant proteins incorporated in ground meats and processed meat products would help to moderate these impacts.

Keywords: Dietary transition; Meat consumption; Efficiency of meat production; Animal feeding; Environmental impacts of intensive animal husbandry; Plant proteins

1. Introduction

Current global market for industrial proteins adds up to only a small share—most likely less than 0.5%—of multifaceted activities that are commonly included in the catchall category of biotechnology [1]. This is bound to change as it is clear that proteins derived from plants or produced by genetic manipulation of crops will find an increasing variety of medicinal, processing and manufacturing applications, ranging from blood-clotting preparations to biodegradable packaging. But there can be no doubt that by far the biggest market for novel plant-derived proteins, no matter if they are merely processed in new ways or if they are bioengineered to acquire desirable characteristics, would arise from their successful large-scale introduction into the world's food system as extenders, supplements and replacements of animal proteins. Use of these novel proteins would have the greatest economic, nutritional and environmental impact if they could replace a relatively modest, but cumulatively significant, share of natural animal proteins consumed as meat.

I am not going to address any biotechnological requirements that have to be met and any practical obstacles and complications that will have to be overcome before such a large-scale adoption of novel proteins could eventually take place. Some of these problems will be solved rather swiftly by new research, others will be certainly more recalcitrant, and yet others, including the production of look- and taste-alike substitutes for common retail meat cuts, perhaps should not be even addressed in the near term. Some of these challenges are now being investigated by PROFETAS [2]—and by a number of researchers attending this meeting.

What I will do—as an interdisciplinary natural scientist interested in interactions of food, environment, energy and public policy—is to look at the coming quest for novel proteins from a wider food supply perspective. This understanding can be used to justify and to promote the necessary research effort. I will first outline the worldwide transformation of typical diets and then I will focus on the enormous, and rising, environmental burden of meat production. Combination of these two realities creates intriguing opportunities for the future use of novel proteins and, in closing, I will offer some order-of-magnitude estimates of potential substitutions and their consequences.

2. Dietary transitions

Several powerful and virtually global trends have been modifying diets around the world. Economic modernization has been the driving force of urbanization. Africa and Asia are now the only two continents where less than half of the population lives in cities—but where the average annual urban growth rates are also the fastest. Continental shares of urban populations in Latin America, North America and Europe are all now very close to 80%. In spite of their widely differing exteriors, urban societies on all continents

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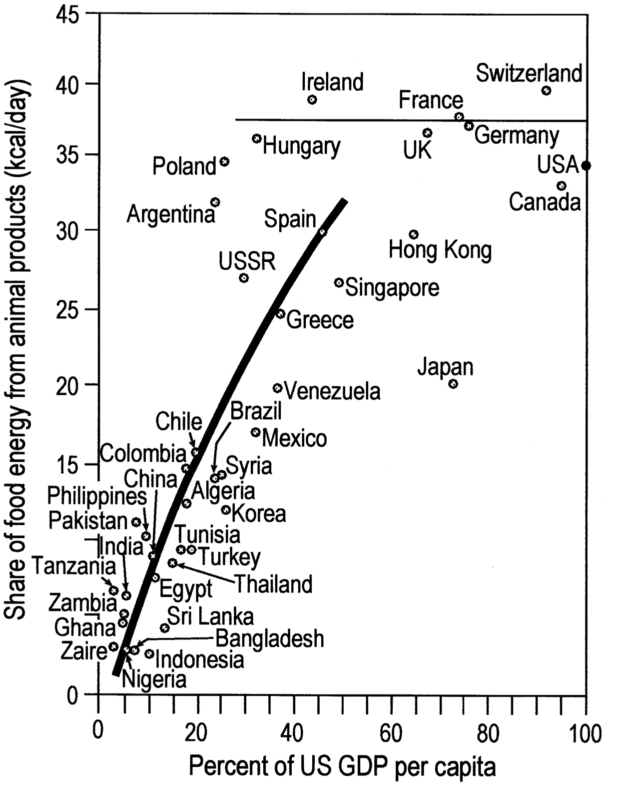

Fig. 1. Shares of available food energy derived from animal foods in relation to national gross domestic product measured in terms of the purchasing power parity [23].

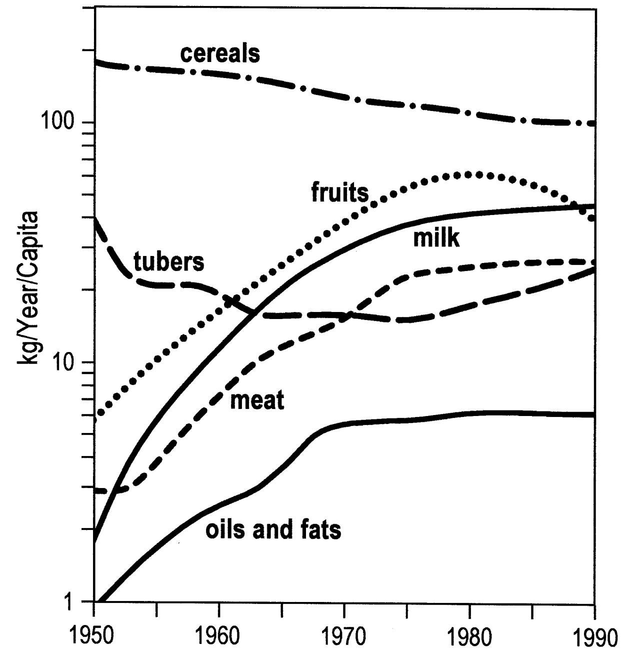

Fig. 2. Dietary transition in two Japanese generations. Plotted from data in Japan's Statistical Yearbook.

share a number of common features and trends driving dietary transformations.

Almost invariably, those urban societies have very high rates of labor force participation of women (commonly in excess of 60%). Their average family size is smaller than in the adjacent rural areas. Urban families include relatively large shares of single-person households and, in all more affluent societies, also of childless professional couples. Urbanites have a lack of time (real or perceived) for leisurely shopping for food and for time-consuming (or often any) cooking (the phenomenon well known to economists as the opportunity cost of time). In general, urban households have considerably higher incomes at their disposal than rural societies. Finally, urban societies are the first ones to be exposed to the effects of growing international trade and intercultural exchange, the two trends that have lead to often remarkably rapid diffusion, adoption and "domestication" of foreign foods.

Moving up the food chain has been the most obvious, and universal, expression of these dietary transformations [3,4]. Affected populations are eating less staple grain directly, but more animal foodstuffs, a trend highly correlated with rising per capita income (Fig. 1). They also consume more plant oils, fruits and vegetables (Fig. 2) and drink more alcoholic beverages. Moving up the convenience chain is a closely correlated corollary of the first trend as much less time is spent shopping for food and in cooking while an increasing share of meals is eaten outside the home and as there is a growing demand for convenience foods or for what is in the food business known as home meal replacements. The result is thus contradictory. On one hand there is considerable enrichment of previously monotonous diets and democratization of taste evident in such diverse ways as mass consumption of tea, coffee and chocolate and a greater attention to the appearance of food. On the other hand is the spreading consumption of mass-produced meals, either those eaten out (in one of the numerous outlets of giant fast food empires) or those rapidly prepared at home.

This dietary transformation advances in several stages. Demand elasticity is particularly high at relatively low-income levels. As a result, in countries whose pre-modernization intakes of staples were barely adequate, the increased disposable incomes usually bring first an increase of average per capita cereal consumption. These gains range from a slight rise among better-off groups to appreciable amounts among the poorest families (only the highest income classes do not participate in this shift). India or Vietnam are at this stage of dietary transition: they still do not enjoy comfortable food supply as their average daily per capita food energy and protein availability are not at least 20–25% above the metabolic requirement compatible with healthy and vigorous living. As the Japanese example shows (Fig. 2), a new consumption pattern eventually emerges, with only minor shifts among major food categories.

Countries accomplish their dietary transition at different paces. Perhaps the only useful generalizations, bearing great similarities to the pattern of demographic transition (from high to low birth and death rates) is that the progression becomes fairly fast once the process advances beyond a

Table 1
Meat consumption in affluent countries (all values are annual averages in kg/capita)

Country	1970	1980	1990	2000
USA	112	112	117	122
Canada	98	99	97	95
Germany	83	100	99	90
France	95	111	110	100
Netherlands	64	76	83	101

Source: FAO Food Balance Sheets (http://apps.fao.org).

Table 2
Increasing meat consumption in modernizing countries (all values are annual averages in kg/capita)

Country	1970	1980	1990	2000
Brazil	31	42	49	68
China	9	14	26	46[a]
Indonesia	4	5	8	9
Mexico	27	42	42	51
South Korea	5	14	26	40

Source FAO Food Balance Sheets (http://apps.fao.org).
[a] Exaggerated official total.

certain stage, and that late starters move commonly much faster than the pioneers (European transition proceeded slowly in comparison to shifts in many Asian countries). Perhaps most notably, China’s urban populations have recently completed this entire process in just a single generation. Urban per capita grain consumption first rose to a peak of more than 130 kg in 1985, but subsequently it fell to less than 85 kg by the year 2000, while the per capita consumption of animal foodstuffs nearly doubled during the same period [5].

3. Meat consumption and its impacts

Much like our closest mammalian relatives, chimpanzees, we are omnivores and meat has always been part of unrestricted (be it by poverty or religious rules) human diets. Regardless of their specific national features, past dietary transformations have invariably entailed higher consumption of animal foods in general, and meat in particular. Except for Japan (with its extraordinarily high fish intake) meat is now the single largest source of animal protein in all affluent nations, and it remains among the most desirable, high-status foodstuffs in high- and low-income countries alike. Not surprisingly, global production of meat has nearly doubled with rising incomes during the past generation, from about 130 million tonnes (Mt) during the late 1970s to almost 230 Mt in the year 2000 [6]. Adjusted for population growth this increase translates to a still impressive 25% gain in average per capita supply.

Meat consumption statistics (based on sales of boneless retail cuts or on actual household eating surveys) may differ substantially from production figures calculated on the basis of slaughter and carcass weights (bone in). Trimming off fat before actual consumption and kitchen waste further lower the actual meat intake. The greatest discrepancy of this kind is presented in the official Chinese statistics, where recent production figures show annual per capita rates surpassing 40 kg, while household surveys show consumption well below 20 kg [5].

Whatever the precise rates may be, we know that in most of the affluent countries annual meat consumption surpasses the average body weight, with the high intakes in excess of 100 kg/capita (Table 1). However, in most instances these consumption rates do not represent any increase compared to a generation ago and even show a slight decrease. In contrast, intakes in populous modernizing countries remain low to very low—but they have been increasing steadily and, in many cases, rapidly (Table 2). Moreover, there is obviously a huge unmet demand not just only in those countries where average meat consumption remains very low (India and Bangladesh are two notable examples), but also in those countries where rural consumption still lags far behind the urban means. For example, consumption surveys in China show per capita intakes of all meat in villages to be less than 2/3 of the still relatively low urban level. Long-range forecasts of actual meat demand are highly uncertain, but even very conservative estimates foresee the global consumption to rise about 50% above the current level during the next two generations.

There is no need to adopt the arguments of militant vegetarianism or to point to the recent problems with BSE and foot-and-mouth diseases to conclude that large-scale, intensive meat production causes serious environmental impacts and that its further extension in modernizing countries will only aggravate an already highly undesirable situation. Inherently low efficiency of converting feed into meat is at the root of these problems. Consequently, maintenance of high-meat intakes in affluent countries and transitions from largely vegetarian to fairly meaty diets in many modernizing nations cannot take place without enormous waste of crop biomass as well as without increasingly worrisome environmental impacts. Commonly used feed-to-meat conversion ratios are expressed in terms of standard units of feed per unit of live weight and they do not convey the real magnitude of biomass and energy losses. These ratios must be properly adjusted to express the feeding requirements per unit of actually consumed meat. They also must take into account the need to raise sire and dam animals. Relative feeding requirements for the three dominant kinds of meat —chicken, pork and beef—are then as follows.

When fed a well-balanced diet (metabolizable energy of 3200 kcal/kg, containing about 21% of protein) cumulative feed/gain ratios of chicken are as low as 1.5–1.8 for lighter birds slaughtered after 4–6 weeks, and between 1.8–2.0 for the birds in the most common 2.0–2.5 kg range [7]. Feed requirements of breeder hens and cockerels, and feed wasted on birds that die before reaching maturity raise the mean by at least 10%. Ratios between 2.0 and 2.2—or between 3.6–4.0 for the edible portion—represent the stan-

Table 3
Typical efficiencies of meat production

	Chicken	Pork	Beef
Feed (kg/kg liveweight)[a]	2.5	5.0	10.0
Edible weight (% of LW)	55	55	40
Feed (kg/kg EW)	4.5	9	25
Food energy (kcal/kg)	1800	3100	3200
Energy conversion efficiency (% of gross energy)	11	9	3
Protein content (% of EW)	20	14	15
Protein conversion efficiency (%)	20	10	4

[a] Typical rates from USDA long-term statistics (see the text).

dard of recent good performance. Typical rates are somewhat lower (Table 3). The US Department of Agriculture has kept long-term records of feeding efficiency ratios (expressed in terms of corn feeding units, containing gross energy of 3670 kcal/kg, per unit of live weight) since the 1930s when the nationwide feed/live weight gain stood above five, identical to that of pigs [8]. Continuous subsequent decline has halved that rate by the mid-1980s; this has been the only case of a steady improvement of a USDA-tabulated national mean of feeding efficiency among the US domestic animals (Fig. 3).

Pig's inherently low basal metabolism makes pork the least feed-intensive red meat. With ad libitum intake of feed, the overall feed/gain rate for North American pigs from weaning to slaughter ranges between 2.5 and 3.5. Rates around 3.0 would be good standard performance with feed averaging about 3200 kcal/kg of metabolizable energy and some 15% of protein [9]. With 55–57% of pig's live weight in edible tissues, adjustment of the numerator from the total live weight to edible energy raises the ratio from 3.2 to about 5.4. Addition of feeding costs of the breeding stock (of its reproduction and maintenance, and of fetal growth and subsequent lactation periods) and adjustments for environmental stresses, disease and premature mortality can raise the overall feed/gain rates quite significantly.

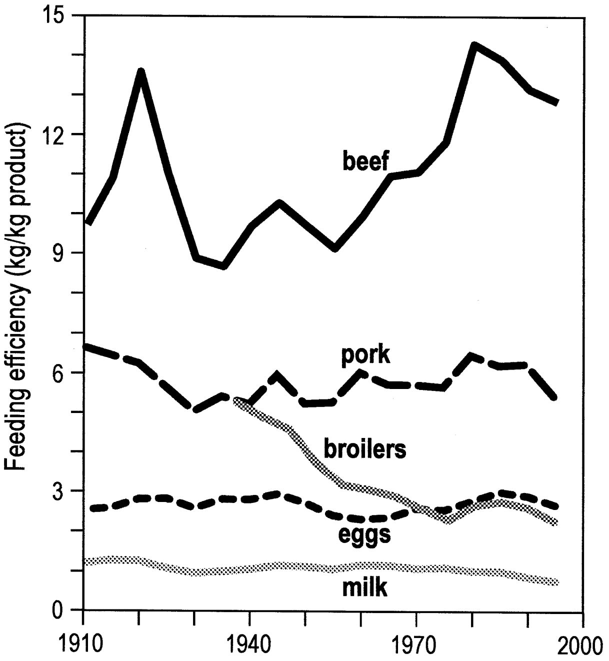

Fig. 3. Comparison of feeding efficiencies (kg of feed/kg of live weight) for US beef, pork and broilers. USDA data [4].

The US Department of Agriculture records show the nationwide feed/live weight gain ratio for pigs at about 6.7 in 1910 and after an initial decline it has fluctuated between 5–6.5 ever since [8] (Fig. 3). The main reason why the trend of continuous improvements in feeding has not been reflected in the national mean has been the quest for less lardy pigs. Leaner animals are inherently more costly to produce per kg of meat: efficiency of metabolizable energy conversion to protein in pigs peaks at about 45%, while conversion to fat can be as much as 75% efficient.

Several bioenergetic realities make cattle the least efficient converters of feed to meat. Their basal metabolism in cattle is appreciably higher than in pigs, and their large body mass and long gestation and lactation periods mean that feed requirements of breeding females in cattle herds claim at least 50% more energy than for pigs, and almost three times as much as in chickens. Calculating comprehensive feed/gain efficiency ratios for beef is a task greatly complicated by a variety of arrangements under which the meat production takes place [10,11]. Only the animals raised solely by grazing do not compete for feed resources with other domesticated species and have no impact on field crop production. Cattle raised without any grazing on commercial feeds (including the minimal share of roughage) are the other extreme of the beef-producing spectrum. After weaning, calves are moved to feedlots where they are fed diet dominated by concentrates combined with feed additives, growth promoters and disease preventers.

These animals gain between 1–1.3 kg a day, growing much faster than grazing animals whose daily gains, even on good pasture, average no more than 0.5 kg. Animals commonly spend between 120–170 days in feedlots before reaching the market weight of 450–500 kg, but many of them are now fed in lots for more than 200 days. For growing and finishing steer and heifers North American and European feed/gain ratios range between 7–9. With 8 as a common mean, and with roughly 40% of live weight in edible biomass, feed energy gets converted to beef with efficiencies between 4–5%, and protein conversion efficiency is around 8 or 9%. Adjusting these rates for the costs of reproduction and growth and maintenance of sire and dam animals raises the feed/gain ratio of herds to over 10. USDA's historic feed/meat data for all of the nation's cattle and calves show an undulating pattern rising and falling between lows of about 9 and highs of 14 (Fig. 3). These rates would mean that as little as 3% of gross energy in feed are converted into energy in food, and that the conversion of feed to food protein is less than 5% efficient (Table 3).

The typical performance record of meat production is thus exceedingly wasteful: 89–97% of gross energy contained in the feed and 80–96% of all protein in cereal and leguminous grains fed to animals are NOT converted to edible protein and fat. Animal husbandry's overall claim on the world's agricultural resources is illustrated most obviously by the rising share of feed grains in the world's cereal production. Total mass of cereal and leguminous grain eaten annually by animals is now surpassing 700 Mt, or roughly a third of the global harvest of these crops, and it contains enough energy to feed more than three billion people.

Of course, this equivalence would be true only if the people were willing to eat a largely vegetarian diet with corn, barley, sorghum and soybeans as staples providing most of their food energy. A more realistic illustration of the claim animal feeding makes on crop harvests is to assume that the area now devoted to feed crops would be planted to a mixture of food crops, and only their milling residues would be used for feeding: this adjustment would mean that roughly an additional one billion people could be sustained on predominantly vegetarian diets containing small, but adequate, amount of animal protein. Needless to say, the actual total of people that would freely chose such a diet could be much lower. A recent report by the Council for Agricultural Science and Technology [12] goes as far as concluding that diverting grains from animal production to direct human consumption would actually result in little increase in total food protein.

Another way to illustrate the impact of large-scale animal feeding on natural resources is to look at the effect of the transition from largely vegetarian to fairly meaty diets on grain production. In traditional societies that enjoy basically adequate nutrition (average per capita supply of 2,400 kcal/day) but derive less than 10% of its food energy from animal foods, such relatively small amounts of meat, eggs and milk require little concentrated feed. In contrast, the same society with a per capita food energy supply of 3,000 kcal/day deriving 25% of all food energy from animals will have to resort to large-scale feeding of grain. Even when this would be done fairly efficiently, supply of 750 kcal of animal food would require at least four or five times that amount of plant feed. This would call for additional output of 3,000–3,750 kcal of crops, or more than doubling of net crop harvests used directly for human consumption (2,250 kcal/day). And this is not an extreme case as there are countries where animal foods now contribute well over 40% of all dietary intake, and where feed grains account for up to 70% of all cereal and legume harvest.

Adequate water supply is emerging as one of the key concerns of the 21st century, and few economic endeavors are as water-intensive as meat production in general, and cattle feeding in particular [13]. Most of these large requirements are due to low conversion efficiencies of feed. Assuming an average of 1000 kg of water to produce 1 kg of feed grain (an average of C_3 and C_4 demands) and about 20 kg of concentrated feed to produce 1 kg of edible beef results in an overall requirement of 20 t of water per kg of meat. From the natural resources point of view one could actually think about international meat trade as a way of avoiding huge water consumption in importing nations. In addition, water used in growing the feed will often end up contaminated by leached and particulate N and P, and water used directly for animal consumption becomes a part of the growing animal waste challenge.

Generation of voluminous wastes by animals is already resulting in introductions of legal limits on their field applications and it is bound to cause even greater environmental stresses in the future. Domestic animals are prodigious producers of organic wastes—but generalizations about their manure output are not easy, as the rates differ with animal breeds, sizes, feed quality and health. Animals are also particularly inefficient users of nitrogen. Even such good protein converters as young pigs will excrete 70% of all ingested nitrogen. Dutch dairy production now utilizes no more than 12–16% of total nitrogen input [14]. Similarly, Bleken and Bakken [15] calculated average nitrogen retention in animal foods in Norway at just about 20%. The worsening environmental impact of manure production stems from a fundamental shift in the structure of animal husbandry, from the still continuing separation of livestock production from field agriculture. In preindustrial agricultures wastes from small-scale animal production using farm-produced feeds were a valued resource critical for maintaining soil fertility.

Recycling of animal, and often also human, wastes in traditional mixed farming kept a substantial share of N, P and K excreted by animals circulating within agroecosystems. Lower harvest indices of unimproved cultivars, which resulted in a larger share of assimilated nutrients retained in crop residues, also helped. But the combination of intensive production of large numbers of animals in confinement and of low-cost synthetic fertilizers turned those wastes from assets to liabilities. In terms of dry solids the global production of animal manures amounted to more than 2 billion tonnes during the late 1990s and, assuming average nitrogen content of about 5%, it contained about 100 Mt of nitrogen.

This represents nearly 20% more nitrogen than is now applied worldwide in inorganic fertilizers derived from the Haber-Bosch synthesis of ammonia (Smil 2001). Unfortunately, this huge mass of an essential plant nutrient is not effectively recycled. Only the wastes produced in confinement are available for economic application to fields. And because the relative nutrient content of fresh wastes is low —mostly between 0.5–1.5% N and 0.1–0.2% P—its handling, transportation and application costs are high in comparison to much more concentrated synthetic compounds. In most instances costs of manure transportation usually limit the distribution of wastes to radii of a few km [16].

Inevitably, waste generated by modern animal husbandry has become a major source of not just local, but also regional environmental pollution. Volatilization of ammonia is the source of objectionable odors from large-scale operations, particularly dairy farms and piggeries; the gas also contributes to both eutrophication and acidification of terrestrial ecosystems following its atmospheric transport and deposition. Leaching of nitrates, contaminating and eutrophying waters, has been given perhaps most of the attention, but accumulation of phosphorus and heavy metals—copper, zinc and cadmium originating in fertilizers used to grow feed crops and in compounds added to animal diet—is also a serious problem. Unlike the first two elements cadmium is not an essential micronutrient. In fact, it is highly toxic and its accumulation in plant tissues is a clear health hazard. In addition, pesticides used to control insects in poultry houses, and antibiotics used in all forms of animal husbandry can be found in manures but we know little about the fate of these chemicals, or their residues, after manure applications.

There are other important environmental impacts associated with meat production. Enteric fermentation in bovines is a major source of methane, a greenhouse gas that is about 270 times more effective as an absorber of infrared radiation than is CO_2 during the first 20 years of its atmospheric residence [17]. But as meat production requires more agrochemicals and more fuel and electricity for manufacturing and operating field and barn machinery its most important impact on global warming is due to CO_2 generated from the combustion of fossil fuels used to make these additional inputs.

Combination of these realities adds up to a convincing conclusion: even if there would be no worrisome livestock-borne diseases, large-scale production of meat based on intensive feeding of highly nutritious concentrates is a practice which is causing numerous environmental problems in affluent countries and its adoption by modernizing nations, particularly in Asia, must be viewed with concern. Challenges of this magnitude and complexity do not have a single miraculous solution, and many approaches will have to combine to moderate the impact of mass meat production.

4. Moderating the impact of meat consumption

Substantial voluntary reductions of meat consumption are not very likely: only concerns generated by the spread of BSE have been able to reduce beef sales, but even such declines are most likely only temporary. Limiting the intensity of animal production is an obvious way to ease the environmental burdens of the practice. After decades of warnings about the impossibility of sustaining environmental burdens of intensive manuring some countries have introduced legislative limits on the practice. Most notably, the Netherlands enacted the limits based on manure phosphorus content, and prescribed better methods of application. Dutch farmers now must comply with norms for manure spreading, slurry soil injection levels and maximum N:P ratio in manure, and they must limit phosphate applications. European Union legislation to control nitrate leaching specifies a maximum number of manure-producing animals per hectare of land available for manure spreading.

Increasing the efficiency of meat production is another obvious goal. The US Office of Technology Assessment [18] identified 41 potentially available techniques that can improve feed, reproductive and production efficiency in beef and dairy cattle, pigs and poultry. Universally applicable routes toward higher feeding efficiency include such basic improvements as better processing of both concentrated and roughage feeds as well as such advanced measures as the use of additives ranging from supplementary amino acids to compounds raising conversion efficiencies. Substituting a portion of animal proteins by proteins derived from crops should be seen as another means to limit animal husbandry claim on natural resources. Practical consideration of this option has been made easier by important shifts in the ways meat is actually consumed: increasing shares of both red meat and poultry are now eaten in the two convenient forms that are amenable to introduction of plant proteins, that is after simple grinding or after more elaborate processing.

Reliable US statistics show that 45% of all retail beef, that is annually over 13 kg/capita, is now consumed as ground meat [19]. This consumption is dominated by a number of well-known hamburger empires whose franchises are now literally encircling the planet and whose sales are still expanding. Shares of pork and chicken used as ground meat are much lower (generally below 10%). Consumption of sausages—including frankfurters (wieners), fresh sausages and cooked or smoked products ranging from low-priced bologna to expensive fermented dry and semi-dry salamis—has been also increasing, in no small part due to the rising popularity of pizza. Annual US consumption of all types of sausages is now surpassing 11 kg/capita, of which nearly 500 g are pepperoni used on pizza [20]. Little has to be said about the truly global appeal of this fast food which is now available with an enormous variety of garnishings ranging from squid and red herring to chicken and wild boar salami.

There are no readily available global statistics of meat consumption disaggregated by final use categories, but my approximate calculations based on a variety of national statistics and known dietary preferences indicate that worldwide at least 15 Mt of meat are consumed after grinding and another 15–20 Mt are used in fabricated foodstuffs. Consequently, some 30–40 Mt of meat are now consumed annually in forms that would make it practical to incorporate varying shares of plant-derived proteins and thus to reduce feeding requirements and to ease environmental burdens of meat production.

Moreover, this partial substitution could begin to make the biggest difference where it would be most welcome: in extending the lean content of ground beef. Although the US is the world's largest beef producer it has recently been importing nearly as much beef (almost one Mt/year) as it exports in order to lower the fat content of its output from about 70–90% range to about 50% in the most popular categories of lean ground beef [21,22]. Given the fact that more than half of all US beef is now consumed either as ground or processed meat I would single out this market as the most promising target for the introduction of plant-derived proteins.

Global impact would naturally depend on the degree of penetration achieved by novel plant proteins. Additions of plant-derived products to animal foodstuffs in the order of 5% of the total fresh mass are already quite common. For example, USDA now allows additions of up to 3.5% of cereal and soy flour or soy concentrate, and up to 2% of soy protein isolates in production of sausages. Consequently, it would not be unrealistic to expect that novel plant proteins could eventually claim at least 25–35% of the fresh mass of ground and processed meats. Recent global consumption has been roughly 40 Mt of ground and processed meat averaging 15% of protein, with an average 20% protein content in mixed (corn and soybean) feed, and with an average 10% conversion rate of plant to animal proteins. Even if suitable novel proteins would eventually supply just 25% of protein content of ground meat and processed meat products this use would lead to a net savings (after taking into account the mass of plant protein that would have to produced or modified as a substitute) of about 70 Mt of concentrated grain feed.

This would be an equivalent of about 10% of recent annual global consumption of concentrated feeds. Even when using the average US yields of corn and soybeans (both being significantly above the global average) this would mean that more than 15 million hectares of land—an area roughly equal to all farmland in Poland or in South Africa—could be either taken out of production or it could be devoted to other crops. Using lower average corn and soybean yields in Latin America or Asia in order to calculate potential land savings could translate to nearly twice that amount of spared farmland.

As there is a great deal of marginal, erosion-prone land that cannot be sustainably farmed (be it the driest zones of the US Great Plains or North China, both of them now producing feeding corn) its retirement due to the savings obtained by the use of plant proteins would have far-reaching environmental benefits ranging from reduced siltation of streams to reduced eutrophication of waters due to N and P lost from fertilized fields. Alternatively, using the land released from feed production for more sustainable uses, such as grazing lands or orchards, or planting it to bioengineered crops producing high levels of micronutrient, would have different, but no less important environmental benefits. And, naturally, reduced feeding of animals would result in lower output of wastes and reduced losses of nutrients to water and to the atmosphere, and less methane.

In order to attain truly sustainable agricultures we will have to rethink and reform most of the practices that prevail today. Their ideal performance should be determined by moving backwards along the production chain, starting with maximum acceptable amounts of nitrate leaching from fertilizers or ammonia volatilization from animal wastes and establishing allowable long-term tolerances of soil erosion and reliable supplies of irrigation water. Only after establishing these rates, and other key environmental parameters, we should determine, given our best practices and technical possibilities, what crops could be grown and what yields should be targeted. Meat production based on concentrate feeding would then emerge as a residue of feedstuffs (plus, obviously, all suitable food processing residues) that could be produced sustainably on land not needed for securing essential food crop requirements.

Before we reach this optimal state of truly environmentally driven agriculture we must explore every opportunity for increased efficiency of entire food chains. Reduced nutrient and water losses during fertilization and irrigation are the most obvious ingredients of such a strategy—but using plant-derived proteins in order to moderate the environmental impacts of meat production should become a major part of this effort as it offers substantial long-term payoffs, benefiting both ecosystems and human health.

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