5

Rationalizing Animal Food Production

We do not have to eat any animal products in order to lead healthy and active lives and to look forward to generous life-spans. But only a very small fraction of humanity adheres to strictly vegetarian diets. Arguments about the desirability of a wider adoption of at least some modified versions of vegetarianism (lacto- or lactoovovegetarianism being the most common choices) have been offered as one of the ways to accommodate larger populations. These arguments have been disparaged as misleading countercultural calls undermining the viability of major sectors of modern agriculture. I have no wish to adjudicate the cultural dimension of these arguments, but resolving the factual question about the comparative merits of vegetarianism and omnivory is easy once one takes energetic and evolutionary perspectives.

The food-chain argument in favor of vegetarianism rests on a straightforward interpretation of an undeniable energetic imperative: eating closer to the Sun will support a larger number of people inasmuch as the interposition of another link in the food chain has to be paid by large metabolic losses associated with animal reproduction, growth, maintenance, and activity. Phytomass used for animal feed would be converted more efficiently if it were consumed directly by humans. This argument would be universally valid if our species had developed multiple stomachs or if our guts carried bacterial communities capable of digesting phytomass containing high shares of hemicellulose and cellulose.

Because none of this is the case, not all domesticated animals compete with people for edible harvests. When cattle, sheep, and goats are grazing on land that should be never converted to crop fields—on semiarid grasslands, slope lands, and mountain meadows—they are not even in any theoretical competition with us, in that the highly cellulosic phytomass of these ecosystems is indigestible by humans. In addition, grassed surfaces provide valuable environmental services by conserving soil moisture and preventing soil erosion. In these cases any objections to harvests of meat and milk based on considerations of human carrying capacity are inappropriate—as long as care is taken to prevent overgrazing and to assure the survival of herds in often highly stressed environments.

Resource competition is also absent, or minimal, in the case of animals grazing on crop residues, on grasses or leguminous cover crops planted in rotation with food species, and fed residues from crop processing and a variety of organic wastes. Again, we could not or would not wish to digest this phytomass, whereas animals metabolize it readily to produce meat, eggs, and milk and wastes whose recycling maintains, or even improves, soil quality.

The carrying capacity argument based on fundamental energetic considerations thus does not exclude appreciable shares of animal food in human diets. The evolutionary argument in favor of omnivory is even stronger. We now know that hunting for meat has an important place—nutritionally and socially—in the lives of both chimpanzee species (*Pan troglodytes* and *Pan paniscus*), and hence also in the evolution of Pliocene hominids (Stanford 1996, 1998). Diet made up primarily of plant foods but supplemented, especially seasonally, by meat is our evolutionary heritage, and strict herbivory is a culturally induced adaptation. The expensive-tissue hypothesis and considerations of practical satisfaction of protein requirements strengthen this conclusion.

Although human brains are much larger than the primate ones, the total mass of our metabolically expensive tissues (internal organs and muscles) is very much as expected for a primate of our size. Aiello and Wheeler (1995) argue that the only way to accommodate larger brains without raising the average metabolic rate was by reducing the size of another metabolically expensive organ. This option is highly constrained in the cases of liver, heart, and kidneys, leaving the gastrointestinal tract as the only metabolically expensive tissue that could vary considerably in size. Indeed, our guts are about 40 percent smaller than they should be in a similarly-sized primate. The primary reason for this difference is that—unlike in the case of herbivores consuming large amounts of low-energy density leaves, roots, and fruits—our diets evolved to include smaller quantities of energy-dense, and easily digestible, foods, including seeds, nuts, and meats.

In those environments where nuts and seeds, which also have relatively high protein content, were readily available, preagricultural foragers could obtain adequate diets by remaining overwhelmingly vegetarian. But in environments where fruits and leaves with low energy density and low protein content made up most of the accessible edible phytomass, satisfaction of basic food energy requirements would have required daily intakes of more than 3 kg of the former and over 10 kg of the latter. Even then this impractically bulky plant diet would have supplied no more than about half of the needed protein (Southgate 1991).

Evidence for human omnivory is provided by numerous anthropogenic studies that have found that the provision and eating of animal foods—be they scavenged (from kills by large carnivores), collected (shellfish, eggs), hunted (from tropical birds to aquatic mammals), or produced eventually by domesticated species—has been a universal ingredient of human behavior with obviously valuable nutritional and social implications. In addition, a relatively recent adaptation—domestication of milking animals—further extended the human consumption of animal foods to include milk and dairy products from at least half a dozen mammalian species (Zeuner 1963; Clutton-Brock 1989).

An obvious conclusion is that our normal diets should contain a variety of animal foods, including meat. Minimum intakes of these foodstuffs can be estimated on the basis of evolutionary considerations. Average consumption of meat among the studied chimpanzee groups (they eat mostly colobus monkeys and also a few other smaller animals) has been between 4 and 11 kg a year (Stanford 1996, 1998). In proportion to body mass, this intake is equivalent to about 6–17 kg a year for humans—a range clearly overlapping with typical per capita meat consumption in preindustrial societies. Per capita rates near the lower end of the range (5–10 kg of meat a year) were common in most peasant societies where meat was eaten no more frequently than once a week and relatively larger amounts were consumed only during some festive occasions. Somewhat higher intakes were found in some pastoral societies and among better-off groups in richer temperate regions with mixed farming.

There would seem to be a good evolutionary argument for the annual presence of at least 10–20 kg of meat in average diets. Looking at traditional per capita intakes in milking societies (leaving such extremes as East African pastoralists, where milk supplied three-fifths to two-thirds of all food energy, aside) suggests annual consumption of dairy products equivalent to around 100 liters of fluid milk. Recent per capita global average for milk supply has been almost 80 liters a year, and meat availability in the mid-1990s averaged about 35 kg.

Both of these levels have been greatly surpassed by all affluent Western societies. During the 1990s population of affluent nations added up to only a fifth of the global total—but these countries produced one-third of hen eggs, two-fifths of all meat, and three-fifths of all poultry and cow milk. Their annual per capita milk supply surpasses 300 kg, and their meat eating ranges from 70 to 110 kg. These rates are up to an order of magnitude higher than in many poor countries—and extending even the current global means to an additional three to four billion people would call for a substantial expansion of animal husbandry.

Better management of grasslands, as well as their mostly regrettable but inevitable extension due to continuing deforestation in Latin America, Africa, and Asia, will provide some of this additional need. Even so, an increasing share of animal foods will have to come from feeding of phytomass grown in direct competition with food crops. This trend has been most obvious in the case of cereals. In 1900 just over 10 percent of the world's grain harvest was fed to animals; by 1950 the share surpassed 20 percent, and it was about 45 percent in the late 1990s. National shares of grain fed to animals now range from just over 60 percent in the United States to less than 5 percent in India. The continuing rise in global demand for meat means that even a larger share of cereals will be fed to animals.

By far the most important means of making diets with a decent share of animal foodstuffs available to billions of additional people would be then to maximize feeding efficiencies, a quest that will at the same time help to lower the claims of animal husbandry on land and water, and moderate its rate of waste metabolism and environmental impacts. A fundamental evaluation of long-term prospects of animal food consumption should set out first accurate comparisons of efficiencies with which animal foods can be produced, and it should also appraise their specific claims on key natural resources. Given a high degree of substitutability among animal foods, such knowledge should help us to introduce more rational ways of their production that would secure the nutritional needs of larger populations with minimal environmental impacts.

Feeding Efficiencies and Resource Claims

Production of milk, meat, and eggs based on feeding crops harvested on arable land inevitably entails a loss of potential food output: edible crops cultivated in place of feed crops would always yield more digestible energy, as well as more protein, than the animal foodstuffs produced from the feed. (However, the plant protein's quality would be inferior to meat, milk and egg proteins; see chapter 7.) Both energy and protein losses caused by inherent inefficiencies of animal growth and metabolism differ substantially among domesticated species—but making accurate comparisons is not as simple as repeating frequently quoted feed/gain ratios.

When they are, as is usually the case, presented without detailed explanation of how they were derived and what they actually represent, these measures are quite misleading. Moreover, the most frequent way of expressing the ratio—units of feed per unit of live weight gain—is not the best means of appreciating energy and protein costs of producing animal foods. I will first calculate these ratios in this common manner—in units of air-dry feed (that is, the phytomass as is usually fed, with only 10–15 percent of moisture) per unit of gain (live body weight or gross product output)—but then I will adjust them to reflect feeding costs per unit of edible product, and express them in terms of energy and protein efficiencies. All these calculations are based on a variety of widely accepted equations and recommendations predicting feed intake of food-producing animals (National Research Council 1987, 1988a, 1988b, 1989, 1994, 1996b).

Protein conversion efficiencies will be given simply as percentages (grams of edible protein per gram of feed protein). But because high-quality protein is the most valuable nutrient in animal foods, I will also express its cost in terms of gross feed energy. Energy conversions will be expressed both in terms of gross energy (GE) and metabolizable energy (ME) of the feed. The former term expresses the energy content of plant or animal-derived feed, and its knowledge is necessary in order to find the burden animal feeding puts on agricultural resources. The second term is the energy in the feed less energy lost in animal feces, urine and gases (Subcommittee on Biological Energy 1981).

In the global ranking of animal foods by mass, cow milk comes first: its annual production is now approaching 500 Mt. Pork, with annual output of about 80 Mt, is by far the most important meat and its output continues to rise. In 1995 the world production of nearly 55 Mt of poultry surpassed the combined beef and veal output, and it will continue to rise steadily while the consumption of the two bovine meats will increase only slowly. Consumption of hen eggs is now at more than 40 Mt a year, and recent rapid growth of aquaculture (a near tripling in fifteen years) has put the combined output of finfish, molluscs, and crustaceans ahead of mutton.

Before following this order of animal food production in discussing specific feeding efficiencies, I must note that all unqualified single figures are misleading. Diversity of breeds, environments, and feeding practices and the necessity of making simplifying assumptions (whose even relatively small uncertainties are magnified by successive multiplications) means that a definite rate is valid only for a particular animal, herd, or flock. These problems are further compounded by wide ranges of average energy densities that could be used in efficiency calculations. For example, average energy densities of pig carcasses range between 3,100 kcal/kg for very lean pigs to 5,500 kcal/kg for lardy animals. To avoid an excessive amount of data, I will calculate values for the best current commercial practices and then point out the lags between these rates and standard performances.

Rates and Trends for Major Animal Foods

Mammalian milk production is an inherently efficient energy conversion process. Feed/milk ratio for the most efficient dairy cows is less than 0.6, which means that, depending on the energy density of their diet, between 55 and 67 percent of gross energy in the feed can end up as food energy in milk. Fat accumulated in cow's bodies can be metabolized to produce milk with even higher efficiency of up to around 80 percent.

Typical performances are obviously less efficient. Feed/milk ratios for most animals on well-balanced diets are between 0.7 and 0.8, and the U.S. nationwide mean is now below 0.8, a 25 percent improvement since the early 1960s (figure 5.1) (U.S. Department of Agriculture 1910–1999). When comparing feed/milk ratios with feed/gain rates for animal foodstuffs produced by nonruminant animals, it must be kept in mind that normal ruminant diets must include adequate amounts and proper composition of roughage that is either indigestible by nonruminant species or can be converted by them with only very low efficiencies.

A general rule with milking cows is that at least one-third of all dry matter feed, or roughly 1.5 percent of the animal's body weight, should be long hay or an equivalent amount of other coarse roughage or silage

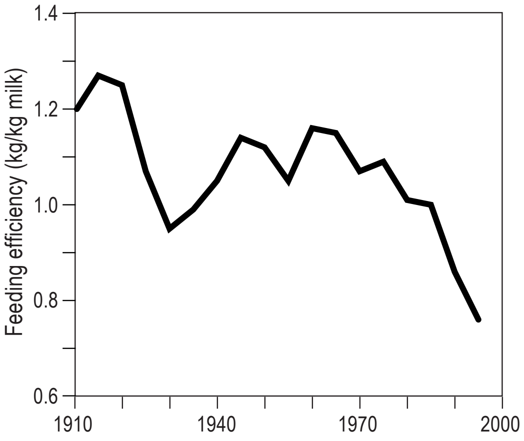

Figure 5.1
Feeding efficiency in U.S. milk production, 1910–1998; plotted from data in U.S. Department of Agriculture (1910–1999).

(National Research Council 1988a). Milk production is thus even more efficient in terms of its claim on resources that could be used as good feed by other animals or directly as food. On the other hand, the overall cost of milk production should be adjusted to include the feed needed to maintain the whole dairy herd.

Depending on the breed, average herd life (from the first parturition to removal) of dairy cattle is between thirty-five and thirty-nine months, equivalent to 3.1–3.5 parities, and to about 1.3 surviving potential female replacements. This means that at least 75 percent of heifers would have to be retained to maintain constant herd size. The retained share is usually higher in order to make possible culling based on first and second parity milk yields and to make up for often considerable mortality, which may exceed 15 percent in some herds.

Moreover, the average age at first calving is twenty-nine to thirty months, rather than the possible twenty-two to twenty-four months. All of this adds up considerably to the feeding cost of dairy herd—but only part of these costs could be attributed to milk production, inasmuch as most of the male calves from dairy herds are now fattened for beef and at least one-fifth of dairy cows is culled annually for meat slaughter.

The most fundamental bioenergetic reason for the high efficiency of pork production is the animal's inherently low basal metabolism. Kleiber's equation, expressing the basal metabolism of mammals as the function of their body mass raised to the power of 0.75, translates into a straight log-log mouse-to-elephant line (Kleiber 1961). Pigs need as much as 40 percent less energy than expected for their weight, whereas basal metabolic rates for cattle lie between the value expected from Kleiber's equation and levels up to 15 percent above it (figure 5.2). As a result, pigs at the midpoint of their growth will channel almost two-thirds of their metabolized energy into weight gain, whereas the share for a 300-kg steer is only around 45 percent, and between 50 and 60 percent for chickens (Miller et al. 1991).

Bioenergetic advantages that make pigs highly desirable producers of meat do not end with low metabolic rates (Pond et al. 1991; Miller et al. 1991; Whittemore 1993). The animals also have a short gestation time and high reproduction rate and grow rapidly. Reproduction usually

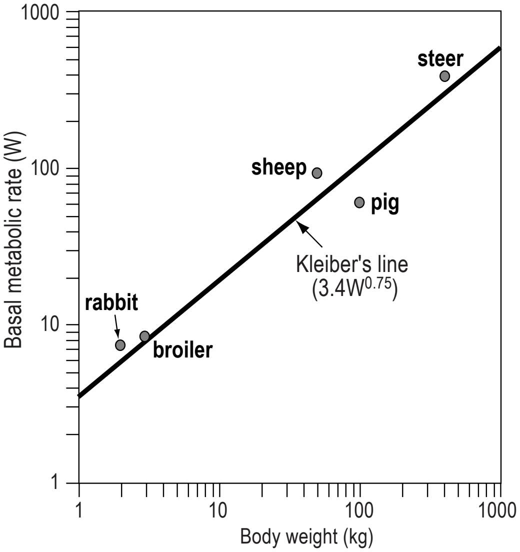

Figure 5.2
Comparison of basal metabolic rates of domestic animals (Smil 1998).

starts at four to eight months of age, pregnancy averages 114 days, and litter sizes range from eight to eighteen. Because the pig's period of gestation is short relative to its life span, its birthweight is a much smaller fraction of its mature weight (a mere 1/300) than in most mammals (Hollis 1993).

As a result, the pig has a very rapid postnatal growth. Piglets are weaned after three to five weeks, and extreme slaughter ages encompass a range from suckling pigs to huge animals used in making Parma hams. Typical slaughter weights in commercial production of modern breeds (90 to 100 kg) are reached 100–160 days after weaning. This means that many pigs are now marketed in less than five months after they are born. Takeoff rate—the number of pigs slaughtered in a year divided by the total number of pigs on farms—measures production efficiency. During the 1990s the rate was in excess of 1.5 in North America and in the European Union (implying an average slaughter age of less than eight months), but just 1.0 in Mexico, 0.8 in China, and only 0.5 in Brazil.

As in other animals, the pig's energy conversion efficiencies decline with age: weaned piglets need only 1.25 kg of feed for a kg of gain, and then the conversion rate of feed to live weight in growing pigs, by definition those between weaning and 70 kg of body weight, rises from less than 1.5 to about 3.0. The rate for finishing pigs, that is, those weighing more than 70 kg but not yet heavy enough for slaughter (at 90–120 kg), is between three and four (National Research Council 1988b; Miller et al. 1991).

With *ad libitum* intake of feed, 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 whose ME averages about 3,200 kcal/kg and some 15 percent of protein (National Research Council 1988b). With 55–57 percent of the 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. The rate would be proportionately lower for the best American operations, which now have feed-to-live weight conversion ratios of about 2.5 (Smith 1997).

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. Perhaps the best long-term record at the national level has been kept by the U.S. Department of Agriculture since 1910 (USDA 1910–1999). They are expressed in terms of corn feeding units (GE of 3,670 kcal/kg) per unit of cattle, pig, and broiler live weight and per unit of produced eggs and milk.

Nationwide feed/live weight gain ratio for pigs was about 6.7 in 1910. After an initial decline it has fluctuated between 5 and 6.5 ever since (figure 5.3). 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: efficiency of metabolizable energy conversion to protein in pigs peaks at about 45 percent , while conversion to fat can be as much as 75 percent efficient.

Birds have inherently higher metabolism than mammals: the difference for identically massive creatures (for example, a rabbit and a hen) will

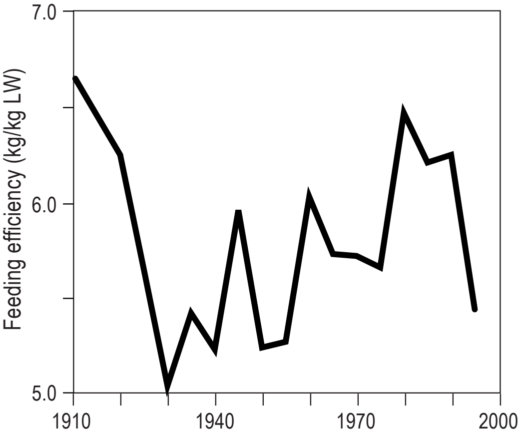

Figure 5.3
Feeding efficiency in U.S. pork production, 1910–1998; plotted from data in U.S. Department of Agriculture (1910–1999).

be up to 10 percent. The higher body temperature of nonpasserine birds—39.5°C vs. 38°C for eutherian mammals—explains most of the difference. Passerine birds have even higher metabolic rates, but no songbirds are reared as meat animals, although plenty of them are caught and eaten in some countries, particularly during their annual migrations. Chickens grown for meat are marketed at ages of four to nine weeks when their body weights range between 0.9 and 3 kg. In the United States the average time needed to produce a broiler was cut from seventy-two days in 1960 to forty-eight days in 1995, while the bird's average slaughter weight rose from 1.8 to 2.2 kg and the feed/gain rate fell by about 15 percent (Rinehart 1996).

When fed well-balanced diet (ME of 3,200 kcal/kg, containing about 21 percent protein) cumulative feed/gain ratios are as low as 1.5–1.8 for lighter birds slaughtered after four to six weeks, and between 1.8 and 2.0 for the birds in the most common 2.0–2.5 kg range (National Research Council 1994). Feed/gain ratios for other common poultry species are somewhat higher, ranging between 2.5 and 2.9 for ducks and between 2.5 and 3.2 for turkeys. Feed requirements of breeder hens and cockerels and feed wasted on birds that die before reaching maturity raise the mean by at least 10 percent. Ratios between 2.0 and 2.2—or between

3.3 and 3.6 for the edible portion—represent the standard of recent good performance.

USDA's (1930–1997) long-term record of feeding efficiency ratios for chickens is available only since the mid-1930s, when the value stood above five, identical to that of pigs. A continuous subsequent decline had 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 U.S. meat animals (figure 5.4).

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 (Orskov 1990; Jarrige and Beranger 1992). The ratios for purely grass-fed beef are of interest to sustainable grassland management, but such animals 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 a diet dominated by concentrates combined with feed additives, growth promoters, and disease preventers. These animals

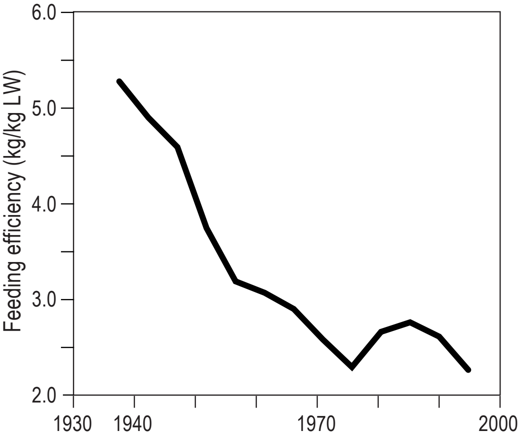

Figure 5.4
Feeding efficiency in U.S. broiler production, 1935–1998; plotted from data in U.S. Department of Agriculture (1935–1998).

gain between 1 and 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 spend commonly between 120 and 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. Feed/meat ratios for growing and finishing calves and yearlings in this kind of operation are usually cited when comparing beef with other animal foods. Naturally, they will represent the most demanding, that is, the least energy-efficient, alternative.

Several bioenergetic realities make cattle less than ideal convertors of feed to meat. As already noted, basal metabolism in cattle is appreciably higher than in pigs. In addition, large body mass and long gestation and lactation periods mean that feed requirements of breeding females in cattle herds claim at least 50 percent more energy than for pigs, and almost three times as much as in chickens. For growing and finishing steer and heifers (calves and yearlings) North American and European feed/gain ratios range between 7 and 9.

With 8 as a common mean, and with roughly 40 percent of live weight in edible biomass, feed energy gets converted to beef with efficiencies between 4 and 5 percent, and protein conversion efficiency is around 8 or 9 percent. Adjusting these rates for the costs of reproduction and growth and maintenance of sire and dam animals raises the feed/gain ratio of herds over 10. The 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 (figure 5.5). These rates would mean that as little as 2.5 percent of gross feed energy are converted into food, and that protein conversion efficiency may be lower than 5 percent. The United States does more of this highly inefficient feeding than any other country in the world. It is, with about a quarter of total consumption, also the world's largest importer of beef.

Performance of modern egg production has improved quite impressively during the latter half of the twentieth century: in the best operations the number of eggs laid per hen has doubled, while the amount of feed needed to produce an egg fell by half. When calculating the

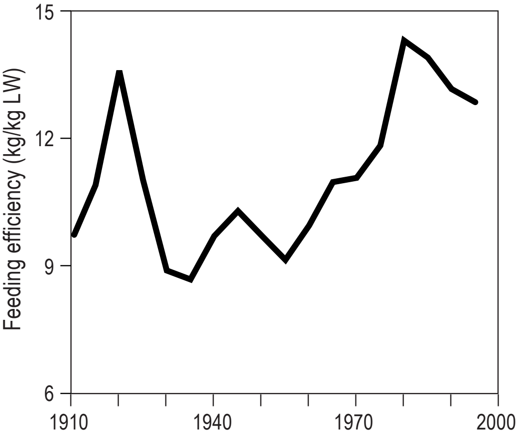

Figure 5.5
Feeding efficiency in U.S. beef production, 1910–1998; plotted from data in U.S. Department of Agriculture (1910–1999).

efficiency ratio for eggs, only the maintenance of the mature laying hen and the nutrition needed to produce egg should be added; requirements of the growing bird before the laying begins should be charged against its eventual use as a low-quality meat source. Feeding rates depend on the hen's body weight (larger birds will, obviously, require more feed for maintenance) and on the rate of egg production (the higher the rate the lower the share of maintenance in egg's feed cost).

Feed/egg mass ratios (based on ME of about 2,900 kcal/kg, with 15 percent of protein) range between 1.8 and 4.1 (Subcommitee on Poultry Nutrition 1994). The most common ratios for Leghorn-type laying hens fed 100–120 g of feed a day and producing eggs nine times every ten days (average weight of 60 g) are between 1.9 and 2.2. The U.S. national ratio has been fairly steady, fluctuating between 2.3 and 2.9 with no discernible trend (figure 5.6).

No food animals are as efficient in converting feed to body tissues as fish (Cowey et al. 1985; Halver 1989; Hepher 1988; Steffens 1989; Barnabe 1994; Parker 1995). There are four major reasons for this primacy. As ectotherms, fish do not have to divert energy to maintain steady bodily temperature. Their low maintenance energy requirements mean that more of their metabolizable feed intake can be diverted to

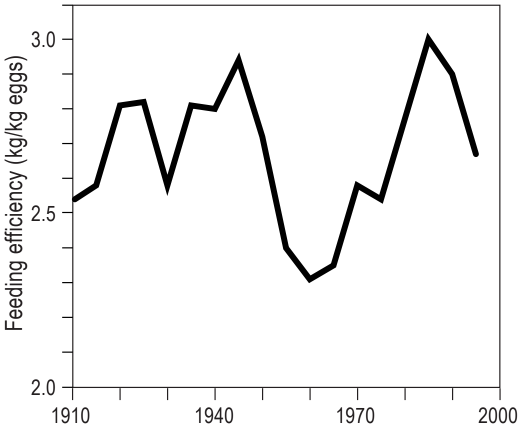

Figure 5.6
Feeding efficiency in U.S. hen egg production, 1910–1998; plotted from data in U.S. Department of Agriculture (1910–1999).

growth than among mammals and birds. Energy costs of locomotion are low inasmuch as life in a buoyant medium does not require large muscles to overcome gravity and inasmuch as streamlined body shapes lower resistance during swimming. Finally, unlike mammals and birds, which spend energy on converting ammonia to urea and uric acid, fish simply excrete most of their waste nitrogen as ammonia through their gills.

Fish need 35–45 percent of protein in their diets, considerably more than either poultry or mammals (Hepher 1988). But their energy needs per unit gain are much lower than in terrestrial species. Conversion ratios for semi-intensively bred carp in warm waters are between 1.4 and 1.8, for catfish between 1.4 and 1.6. Danish statistics show that the average for all intensive freshwater fish farms is almost exactly 1.0 (Ministry of Environment and Energy 1997). Feed/gain ratio for Norway's Atlantic salmon declined from 2.3 in 1972 to 0.9 in 1994 (Blakstad 1995).

Because this reduction was achieved not only by improved breeding and better management, but also by feeding more energy-dense meals (4,700 kcal/kg in 1995, compared to 3,500 kcal/kg in 1972), the actual efficiency gain was somewhat smaller. Still, in terms of edible salmon, the conversion ratio almost doubled, from about 19 percent to about 36 percent.

Comparisons of Efficiencies and Resource Claims

No domesticated animal can produce edible energy and high-quality protein with higher efficiency than a dairy cow (figure 5.7). Highly productive animals convert at least 20 percent of their gross, and more than 30 percent of metabolizable, feed energy to edible energy in milk's lipids and carbohydrates, and between 30 and 40 percent of feed protein is converted to milk protein. Hen eggs from the most efficient layers take an overall second place. Comparisons of feeding efficiencies indicate that pig is the most efficient domesticated animal for converting feed energy to meat (table 5.1): with the best rates of more than 20 percent of metabolizable energy deposited in edible tissues, its performance is superior to that of cattle, and it is well ahead of the rate achieved by poultry.

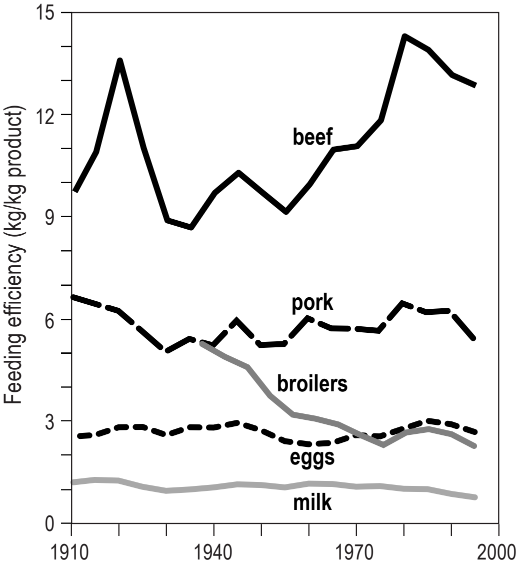

Figure 5.7
Comparison of feeding efficiencies in U.S. milk, meat, and egg production, 1910–1998 (based on figures 5.1 and 5.3–5.6).

Table 5.1
Efficiencies of Animal Food Production

	Milk	Eggs	Chicken	Pork	Beef	Carp	Salmon
Feed (kg/kg LW)	1.0	2.5	2.5	4.0	8.0	1.5	0.9
Edible weight (% of LW)	95	90	55	55	40	65	65
Feed (kg/kg EW)	1.1	2.8	4.5	7.3	20.0	2.3	1.4
Food energy (kcal/kg)	650	1,600	1,800	3,100	3,000	1,200	2,200
Protein content (% EW)	3.5	13	20	14	15	18	22
Energy conversion efficiency (% GE)	20	15	10	15	4	10	30
	25	20	15	20	5	15	35
Energy conversion efficiency (% ME)	30	20	15	20	6	15	35
	40	25	20	25	7	20	40
Protein conversion efficiency (%)	30	30	20	10	5	20	40
	40	40	30	15	8	25	45
Protein conversion efficiency (MJ/g)	0.3	0.3	0.3	0.6	2	0.15	0.1

But we have never produced meat simply for its food energy, but rather for its palatability, attributable to incorporated lipids, and for its protein content. Again, pig is the most efficient converter of feed energy to edible lipids—but in terms of feed energy costs per unit of edible protein, chicken leads. The most efficient broilers need less than 1.2 Mcal/kg of protein, while pigs require more than twice, and beef cattle about seven times as much. The same ranking prevails when the efficiency is expressed in terms of edible protein per unit of gross feed protein.

Animal husbandry's overall claim on agricultural resources is illustrated most obviously by the already noted rising share of feed grains in the world's cereal production. Total mass of cereal and leguminous grain now eaten annually by animals (more than 700 Mt during the late 1990s) contains enough energy to feed more than three billion people—but only if they 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 comparison, assuming that the area now devoted to feed crops were planted to a mixture of food crops, and only their milling residues were used for feeding, would lower this estimate to about one billion people on predominantly vegetarian diets.

Direct land claims of farm animals—for their barns, sties, coops, yards, and enclosures—are only a small fraction of indirect requirements necessitated by production of feeds. For example, an optimum allotment of space for growing and finishing pigs is about one m^2/head (National Research Council 1987); the two animals that occupy sequentially that area during one year will consume at least 600 kg of feed, which, assuming that the pigs are raised on a mixture of concentrate feed, will need on the order of 1,000 m^2 of arable land to grow. Even if we quadruple the amount of space per housed pig in order to account for corridors, accesses, stores, and yards, the difference of two orders of magnitude remains unchanged.

Farmland needed to grow feed for animals is not simply proportional to specific conversion efficiencies. To begin with, a significant share of feeds comes from by-products generated by processing (above all oilseed pressing and grain milling) of food crops, and this contribution should be subtracted from the feed total because its provision does not take away any arable land potentially usable for food crops.

An additional adjustment for a noncompetitive share of feeds must be made in the case of ruminants in order to account for their necessary consumption of straw and grass. Given a great variety of concentrate feed mixtures, differences and fluctuations in feed crop yields, and variability of feed shares supplied by by-products and ruminant roughages, it is not surprising that the values of competitive footprints of animal feeds can range two- or even threefold.

To calculate representative North American means, I have used a weighted average for typical yields of concentrate feed crops, assumed a common share of 20 percent of the total coming from by-products and the minimum 15 percent share of ruminant roughage, and applied these factors to the previously derived efficiency comparison. Once again, milk ends up first, with as little as one m^2 of farmland needed to produce one Mcal of food; eggs are about 50 percent more demanding and pigs are not far behind (table 5.2). Production of chicken meat needs twice as much land as milk, and beef demands at least six times as much.

But chickens need the least amount of space to produce a unit of protein (of course, it helps that, carnivorous fish aside, their meat has the highest protein content of the all animal foods), closely followed by eggs and milk. When comparing on the basis of lean meat, cattle may require more than 20 m^2/Mcal when fed with grain grown in drier regions with lower average crop yields, and they may need up to twenty times as much as space as chickens to produce the same amount of protein. But pasture-fed cattle that receives only a small amount of feed protein supplement may demand no more arable land per unit of edible energy than do broilers or pigs.

As in the case of land requirements, total volumes of water needed to grow feed crops are orders of magnitude higher than the direct consumption by animals—but the presence of thousands of heads of

Table 5.2
Comparison of Land Requirements of Animal Foods*

	Milk	Eggs	Chicken	Pork	Beef
Space per unit of food energy (m^2/Mcal)	1–1.5	1.5–2	2.5–3	2–2.5	6–10
Space per unit of food protein (m^2/kg)	19–28	19–25	13–15	80–100	180–310

* Assuming average feed crop yield of 6 t/ha.

large animals and tens of thousands of birds in feedlots and barns requiring *ad libitum* water supply adds up to considerable quantities. These needs vary greatly with prevailing diet, productivity, and ambient temperature.

For example, a small cow producing less than 20 kg of milk a day will need less than 100 kg of water, whereas a 600 kg animal producing 30 liters of milk will need about 150 kg of water in spring, but more than 300 kg in summer. Poultry has by far the lowest water requirement: a growing broiler needs just 1–2 liters of water a week, egg-laying hens 500–800 ml (National Research Council 1994). On the other hand, water needs of dairy cattle are higher in relation to their size than for any domestic animal. For nonlactating animals they equal three times their dry matter feed intake in cold temperatures, and the multiple rises to about five when the temperature is around 25°C; afterward there is an even faster increase to the multiple of 15 at 35°C. When lactating, the animals will require additional 2.2 liters for every kg of milk produced at 10°C, and over three liters at 30°C (National Research Council 1988a).

I have calculated ranges of typical water requirements per unit of edible foodstuff for animals in temperate climates and relative differences are very similar in both energy and protein terms. Beef requires roughly three times as much water as milk, which, in turn, is two-three times as demanding as pork; water cost of edible energy and protein in eggs are a mere one-twentieth to one-fiftieth of those for beef (table 5.3).

Table 5.3
Comparison of Water Requirements of Animal Foods

	Milk	Eggs	Chicken	Pork	Beef
Water per unit of food energy (g/kcal)	10–15	1.5	6	5	25–35
Water per unit of food protein (g/g protein)	200–300	15	50	150–200	700–800

Obviously, aquacultural water requirements are comparatively large. Those for shrimp cultivation are particularly high, between 50,000 and 60,000 tonnes per tonne of shrimp. In ponds with intensive production about a third of water has to be changed daily, and about half of it is fresh water needed to obtain the optimum salinity level. Not surprisingly, groundwater levels of several coastal regions dotted with shrimp ponds have been dropping rapidly. Large-volume pumping of freshwater and seawater also effects the biodiversity of affected areas.

Finally, a resource constraint peculiar to animal farming is its generation of voluminous wastes, which is already resulting in introductions of legal limits on their field applications and which 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, inasmuch as the rates differ with animal breeds, sizes, feed quality, and health.

In relative terms (per kg of live weight) dairy cows are by far the largest producers of feces and urine, followed by beef cattle, poultry, and pigs. Annual waste production from a dairy farm with 1,000 animals will amount to around 20,000 t of feces and urine, with solids accounting for about 14 percent of this total. Animals are also particularly inefficient users of nitrogen. Even such good protein convertors as young pigs will excrete 70 percent of all ingested nitrogen. Dutch dairy production now uses no more than 12–16 percent of total nitrogen input (Steverink et al. 1994). Similarly, Bleken and Bakken (1997) calculated average nitrogen retention in animal foods in Norway at just about 20 percent.

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 renewing soil fertility. Recycling of animal, and often also human, wastes in traditional mixed farming, as well as lower harvest indices of unimproved cultivars (which resulted in a larger share of assimilated nutrients retained in crop residues) kept a substantial share of N, P, and K excreted by animals circulating within agroecosystems.

Manures, when properly stored and applied, are a very valuable ingredient of rational food production. Their application results in similar or higher crop and pasture yields as those obtained through the use of inorganic fertilizers (Choudhury et al. 1996). In areas with concentrated poultry or pig production (prime U.S. examples are the Delmarva peninsula and western Arkansas for poultry) manure could supply all nutrients needed by all crops. 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 Gt during the mid-1990s and, assuming average nitrogen content of about 5 percent, it contained about 100 Mt of nitrogen. This is an impressive total, but not all of these wastes are available for collection and recycling: most of the world's cattle, camel, horse, sheep, and goat manure is not produced in confinement. And because the relative nutrient content of fresh wastes is low—mostly between 0.5 and 1.5 percent N and 0.1 and 0.2 percent 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 (Sims and Wolf 1994).

As is the case with housing the animals, space to store wastes is a small fraction of the area claimed by cropland, but manure applications to fields face growing limitations. Because of the continuing concentration of animal production—for example, six Midwestern states produce about two-thirds of all U.S. pork, and some four-fifths of all U.S. pigs are now fed on farms selling a thousand or more animals a year—cropland in some regions, and particularly in the vicinity of the largest enterprises, may become rapidly saturated with organic wastes.

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. 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.

Copper and zinc levels are usually highest, and cadmium levels are typically two orders of magnitude lower. Unlike the first two elements, cadmium is not an essential micronutrient; 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. We know little about the fate of these chemicals, or their residues, after manure applications.

After decades of warnings about the impossibility of sustaining environmental burdens of intensive manuring, some countries have begun legislated limits on the practice. Most notably, the Netherlands enacted limits based on manure's phosphorus content and prescribed better methods of application (Archer and Marks 1997).

Wastes that are not recycled to fields could be used *in situ* as substrates for methane generation or microbial or protein synthesis, or turned into feed ingredients. The first two options, technically well proven, are economically unappealing. The third one has potentially by far the highest economic return because of the relatively high nutrient content of some wastes, particularly poultry litter and pig excreta: dry-matter crude protein content of these wastes is as high as 25–30 percent, and they have also high concentrations of many minerals (Fontenot et al. 1996).

Numerous experiments have shown that feeding of wastes does not adversely affect either the quality or taste of meat, or milk composition or flavor. Safe utilization, however, requires that wastes be free of drug residues and that they be properly processed (by heat treatment or ensiling) in order to destroy potential pathogens. Ruminants are the best animals to use high-fiber wastes of other species. Environmental benefits of this practice can be high because up to 60 percent of its dry matter can be digested by cattle.

Opportunities in Milk and Meat Production

Given the variety of livestock systems around the world, different concerns will dominate future development. The two extremes are highly intensive production systems prevalent in affluent countries and in parts of Asia, and low-intensity production in the humid and subhumid tropics (Sere and Steinfeld 1996). Intensive systems, now producing more than half of all meat by raising mainly pigs and poultry on well-balanced mixtures of prepared commercial feeds, have severed the traditional integration with field cropping: they do not engage either in feed production or in the disposal of manure on farmland. At the same time, they are vulnerable to fluctuating costs of commercial feeds and are handicapped by concentrated volumes of waste that they generate. Producing in saturated (or declining) markets, their primary goal is to use existing inputs with higher efficiency and to deal effectively with environmental effects of their operations.

In contrast, management in the humid and subhumid tropics and subtropics has to concentrate on higher production rates and on improved feeding efficiencies in order to meet the demand of growing populations. Its most important challenge is the adaptation of traditionally proven systems where animal husbandry has been integrated, through feeding of diverse phytomass and recycling of organic wastes, with field farming. Its greatest opportunities are in increasing the output of the three most efficiently produced animal foodstuffs, milk, pork, and chicken. A particular Asian concern is the transformation of water buffaloes from working animals to valuable meat and dairy species.

More Efficient Feeding

There is no shortage of means to improve animal feeding. The U.S. Office of Technology Assessment (1992) identified fourty-one potentially available techniques that can improve feed, reproductive and production efficiency in beef and dairy cattle, pigs, and poultry. Its forecasts predicted gains in feed efficiency rising at an annual rate of 0.39 percent for dairy cattle and up to 1.63 percent for pigs during the 1990s. There is no reason why somewhat lower gains should not follow in the new century. Universally applicable routes toward higher feeding efficiency include such basic improvements as better processing of both concentrate and roughage feeds and such advanced measures as the use of additives ranging from supplementary amino acids to compounds raising conversion efficiencies.

Proper processing of concentrates is universally helpful: it requires not only requisite capital investment but also considerable expenditures of energy for moisturizing, steam flaking, exploding, gelatinization, roasting, grinding, and pelleting of grains and oil meals. These investments are repaid by increased efficiency with which the concentrates are converted to animal foodstuffs. Most low-income countries could achieve substantial efficiency gains by pursuing this course.

At the same time, feeding every suitable organic waste will obviously maximize the overall efficiency of the entire food chain. There is a large assortment of these materials, and as commercial processing of crops becomes more widespread they are continuously, or seasonally, available in considerable quantities. Using these wastes requires additional management and storage, but in return the producers in the proximity of processing facilities can get good quality residual feeds (peanut skins, rice bran, distillers grains) or inexpensive roughages (citrus pulp, cottonseed hulls).

Dairy production everywhere can benefit from better harvesting, storage, and feeding of roughages. This phytomass still supplies most of feed energy in poor countries, and although concentrates now provide as much as 70 percent of all dairy feed in rich countries, forages remain indispensable in milk production. Their quality matters as they provide large shares of feed energy and minerals, and as their inherently lower digestibility has a great influence on overall productivity. In order to ensure high nutritive value, forage cultivars should be selected for high digestibility (low lignin content), harvested at appropriate time, and stored in ways maximizing nutrient recovery.

This requires close attention both to harvesting and preserving of the feed. Attention to such variables as dry matter content of the forage, stage of kernel maturity in grain feeds, and leaf-to-stem ratio in alfalfa is critical to harvest high-quality forage. Plant and microbial enzymes will take their toll on stored forages, and even good ensiling and haying practices will end up with losses of up to 20 percent of the original dry matter.

Correct moisture for ensiling, quick filling and tight packing of silos, and careful sealing of ensiled phytomass will minimize the losses by limiting the period of high microbial activity. Fairly tight seals, assuring anaerobic conditions, are relatively simple to provide, and they are particularly rewarding in smaller storages: because most of the damage due to feed oxidation takes place in the uppermost meter of silo, the resulting loss of dry matter will be relatively much larger in smaller storages. Rewards for tight seals are high: young Holsteins could gain between 100 and 200 g more a day when fed alfalfa from a tightly covered silage as opposed to feed coming from uncovered silos (Staples 1992).

Appreciable loss of dry matter (anywhere between 5 and 15 percent) is inevitable as hay drying reduces the moisture from about 80 to less than 20 percent. Solar radiation, ambient temperature, and air and soil moisture are critical drying factors beyond a producer's control. Still, a few simple measures—such as harvesting smaller batches of peak-quality forage rather than waiting for an assured period of prolonged dry weather, or mowing early in the day to maximize the available drying time—can make a big difference.

Improper hay storage may undo all the effort of good harvesting. Baling of wet (more than 20 percent moisture) forage encourages mould growth and damage to plant proteins from excess heat production (even spontaneous combustion is possible). Rewards of proper storage are high: for example, alfalfa baled at more than 20 percent moisture can lose nearly twice as much dry matter as the crop stored with moisture below that critical level (Mader et al. 1991). As with farm-produced forages, a proper storage and timely feeding of commercial feeds can prevent considerable losses, particularly with such moist matter as brewers grains (60–80 percent water content).

Enhancing the digestibility and palatability of roughages offers yet another route toward higher efficiency of feeding. Common chemical treatments of straw include hydrolysis using sodium hydroxide, ammonia or urea, or oxidation. Digestibility of crop residues can be also greatly improved by delignification (done through solid-state fermentation with white-rot fungi), treatment with purified enzymes (degrading cellulose and hemicellulose), or bacterial inoculants (Fahey et al. 1996).

Considerable efficiency gains can be realized as dairy farmers outside affluent countries move away from relying solely, or largely, on selfproduced forages and raw concentrates and begin feeding premixed commercial feeds formulated to deliver accurately balanced nutrition. Consistency of these feeds is another advantage; although bovine rumen helps to even out daily fluctuations in nutrient intakes, even ruminant productivity suffers as a result of inconsistent rations. This shift toward a higher share of commercial feeds should help to narrow the gap between the rich and the poor world's typical dairy productivities. Average milk yield in rich countries (on the order of 4,500 kg a year per animal) is now more than four times the global mean and more than ten times the average for sub-Saharan Africa.

With pork accounting for two-fifths of all meat consumed worldwide, improvements in feeding represent a particularly rewarding investment in research. Taking advantage of the pig's proverbial omnivory is an important approach, above all in land-scarce countries. Pigs now consume about half of the U.S. corn harvest. They gain well on sorghum when the grain is incorporated into a mixed feed; in northern latitudes they are often fed barley (a feed inferior to corn) and potatoes, whereas in the tropics a combination of cassava and a protein supplement works as well as the corn-soybean meal (Pond et al. 1991).

Pigs find both wheat and rice brans highly palatable, and consume a variety of distillery and brewery by-products. Other good carbohydrate feeds include sweet potatoes, bananas and plantains, cane sugar, and molasses. Both animal fats and many oilseed meals make good feeds, as do blood and fish meals. Properly treated (thoroughly boiled) food wastes are a common pig feed. Naturally, young pigs reared only on garbage, a feed of low energy density with low protein content, grow slowly compared to animals fed good concentrate feeds: where garbage constitutes a large share of pig feed, market weight may not be reached in fewer than eight to ten months. The pig's omnivory presents tremendous opportunities for tapping currently underutilized or wasted feed resources, ranging from unmarketable bananas to leucaena leaf meal and from cocoyams to seaweeds (Thacker and Kirkwood 1990).

These alternative feeds are available particularly in tropical countries, many of them being high-yielding crops of lower nutrient density than grains, but produced with higher photosynthetic efficiency (sugar cane, water plants, tree crops). For example, bananas can be a substantial source of carbohydrates, for 10–50 percent of the total crop in major exporting countries are rejected for human consumption (Ravindran 1990). When combined with a protein supplement, ripe waste bananas can provide up to three-quarters of all dry matter intake in growing and finishing pigs, while dried green fruit can substitute up to half of all grain in usual diets.

Sophisticated manipulation of individual nutrients, or of their constituents, can result not only in significant conversion gains but also in substantially reduced waste. Genetic manipulation of crops or adjustments of protein quality could lower or eliminate the presence of nonessential amino acids and produce feeds with more fitting proteins that would generate less waste nitrogen. For example, every gain of 0.25 percent in feeding efficiency of pigs reduced their nitrogen excretions by 5–10 percent. Formulation of diets with synthetic amino acids in order to provide requisite levels of protein while avoiding overfeeding can reduce total nitrogen excretions in urine by as much as 25–30 percent. Lysine and methionine are already common feed additives; threonine and tryptophan will follow.

Nitrogen utilization in ruminants can be improved by using beta-agonist drugs and a growth hormone (bovine somatotropin, BST) whose intakes, singly or combined, cause appreciable increase in nitrogen retention (Sillence 1996). BST is produced by bacterial fermentation, and its implantation or injection to lactating cows increases their milk production by up to 40 percent. Higher feed and water requirements are more than compensated by higher milk output and by higher feed efficiencies.

BST also improves feed conversion in beef feedlots by about 9 percent and increases carcass lean content by the same amount. The use of BST has been highly controversial (Fallert et al. 1987; Jarvis 1996), but its future large-scale production could lead to worldwide use, as well as to its extension to sheep, goats, and water buffaloes (the hormone boosts production in hot climates). Feed efficiencies in ruminants can be also increased by addition of antibioticlike compounds produced by *Streptomycetes* fungi, which alter the metabolism of several ruminant bacteria and decrease energy loss as methane, saving about 10 percent of feed (Bent 1993).

Because about two-thirds of plant phosphorus is locked in phytic acid, a compound almost indigestible to monogastric animals, increased availability of phytase, the requisite hydrolytic enzyme, will reduce phosphorus excretion. Only wheat has plenty of the enzyme, while corn, sorghum, and most other feedstuffs are relatively phytase-deficient, and hence additions of microbial phytase, commercially available in the Netherlands since 1991, is very helpful inasmuch as it can increase phosphorus utilization by 20–30 percent (Jongbloed and Henkens 1996).

Better Management

Improved feeding efficiencies are far from being the only goal of more rational production of animal foods. Conversion of feed to lean meat is less efficient than the conversion to fat, but leaner meat is nutritionally much more desirable. The relative ease with which we have manipulated the lean/fat ratio in pigs is an excellent example of better management pursuing the goal of healthier nutrition.

When lard was a popular fat pigs were bred accordingly; as plant oils have virtually eliminated lard as a kitchen fat, and as more health-conscious consumers began demanding less fatty meat, leaner pigs came to dominate the market. The pig's genetic plasticity made it possible to achieve many desired changes fairly rapidly, over the course of twelve to twenty generations. For example, U.S. breeders reduced the average lard weight from about 14 percent of the carcass in 1960 to less than 5 percent by 1983. Total fat was reduced from 30 percent of carcass in the early 1960s to less than 15 percent by the early 1990s, with the subcutaneous layer of fat declining by 0.5 mm a year to as little as 12 mm in mature animals (Pond et al. 1991; Whittemore 1993). Choice, prime-grade, boneless cuts of pork have between 25 and 35 percent less fat than similar cuts of beef.

Pigs have other advantages for universally better management. Unlike cattle—whose production suffers in the tropics due to persistent parasites and in large parts of tropical Africa due to the presence of the tsetse fly—pigs tolerate a wide range of environments and can be reared in climates ranging from the subarctic to the equatorial. Also unlike cattle, whose best temperate breeds do not readily adjust to hot environments, pigs bred for temperate climates adapt easily in the tropics, and hence the selection of the most productive animals is merely a matter of transfer rather than lengthy breeding requiring incorporation of indigenous genes.

Other measures that can result in higher dairy production range from very simple environmental manipulations to novel genetic interventions. Extending the exposure of cows to light is a surprisingly effective way to improve lactation, growth, and reproduction. Lactating cows living with sixteen to eighteen hours of light a day produce 5–16 percent more milk than the animals exposed to twelve to thirteen hours of light. Supplemental light boosts winter production in all latitudes beyond the tropics. Fluorescent lights should be used in facilities with low ceilings, and high-pressure sodium lamps can be installed in buildings with high ceilings or in open corrals.

Advances in dairy research also promise many less controversial improvements than the use of BST. As many cow embryos are currently not carried to term, improvement in reproduction rates brought by better understanding of uterine and embryonic synchrony will be an important source of increased efficiency. Dairy production will be also enhanced by better vaccines against common pathogens and by genetically engineered protein used in treatment of diseases.

Throughout monsoonal Asia, and elsewhere in humid tropics, much greater research and breeding attention should be paid to water buffaloes (*Bos bubalis*). These docile animals are well adapted for tropical and subtropical climates. Because of the higher count of cellulose-breaking bacteria and protozoa in their guts, they also use low-grade roughages more efficiently than both *Bos taurus* and *Bos indicus* cattle (Cockrill 1974; Rao and Nagarcenkar 1977). As a result, their overall feed/gain ratios, typically ranging between 5 and 7, tend to be lower than in cattle. In addition, buffalo milk is richer in protein and fat than cow milk, but both average milk and meat yields are far behind the means for temperate-climate cattle.

Potentially significant changes requiring better management of domestic animals may come because of rising concerns about animal welfare. These concerns should not be dismissed merely as the emotional outbursts of vegetarian activists. After all, all domesticated species used for food production are social animals with well-developed group organizations, and modern farming obviously disrupts these arrangements in ways ranging from overcrowding to complete isolation (Mench and van Tienhoven 1986). Resulting stresses, as well as density-promoted disease, contribute to their discomfort.

Crowding is most obvious in poultry and hen production. Broilers and laying hens reared by groups of many thousands in tightly spaced cages can have as little as 450–500 cm^2 per bird. In contrast, free-range hens may have as much as 25 m^2 of grass per bird, or five hundred times as much space—but because of their higher metabolism they will consume up to 20 percent more feed than their caged counterparts (Appleby et al. 1992). Free-range hens will also produce about 10 percent fewer eggs, and hence their feed/egg ratio is 25–30 percent higher than for the caged birds.

Aquacultural Possibilities

Biospheric imperatives—above all the scarcity of macronutrients in surface waters—limit the annual primary production of the open ocean to just between 50 and 100 $g\,C/m^2$, resulting in fish yields of well below 100, and commonly less than 10, kg/km^2. Fish yield on continental shelves is, on the average, two orders of magnitude higher, and that of ponds is ten times higher still. Annual global catch has averaged about 100 Mt, of which about 30 percent are reduced into fish meals, oils, and other industrial products for nonfood uses.

During the late 1990s the world's average per capita supply of some 14 kg of fish, molluscs, and crustaceans contained only a few percent of all available food energy, but it supplied about one-sixth of all animal protein. The latter share is much higher regionally: aquatic species provide more than a third of animal protein to at least two hundred million people, mostly in East and Southeast Asia. Yet the natural foundations of this valuable harvest have become seriously endangered (Safina 1995; FAO 1997).

After several years of slight decline and stagnation, the total marine catch rose once again in the mid-1990s, but further substantial increases are unlikely. Indeed, a conservative assessment of the global marine potential concluded that as of the year 1996 the world ocean is being fully fished (FAO 1997). This means that a large share—about 60 percent of some two hundred major marine fish resources—has been either overexploited or is at the peak level of its sustainable harvest.

The Atlantic Ocean has been fully fished since 1980. The Pacific reached that threshold before the year 2000. Only in the Indian Ocean are there still opportunities for increased catch. That is why more optimistic assessments of global marine potential foresee a possibility of substantial increase (on the order of 15–20 Mt/year). But these forecasts rest on weak foundations, and even relatively major gains in the Indian Ocean may be more than negated by the sudden collapse of mature or senescent fisheries. As far as North Sea cod stocks are concerned, even a regimen close to the maximum sustainable yield may be prone to risk (Cook et al. 1997).

The only prudent course is then to assume that long-term marine catches should not be boosted above the recent rate of 80–85 Mt a year. Even if this level of fishing could be maintained during the first half of the next century, population growth would cut per capita fish supply by up to 50 percent (Population Action International 1995). This brings an obvious question: can expanded aquaculture fill most, if not all, of the rising demand for finfish, molluscs, and crustaceans?

Potential Gains

Unlike with our thousands years of experience with land animals, relatively large-scale and widespread breeding of aquatic species, and particularly of ocean finfish, is a very recent phenomenon outside the areas of traditional Asian aquaculture. This means that the recent trends of rapid expansion characterizing aquacultural developments in the United States and Canada, in both the Atlantic and Mediterranean Europe, and in parts of Latin America are poor predictors of future developments.

These trends may subside in the near future, or they may persist, with inevitable downturns, to make aquaculture a major contributor to global nutrition of the twenty-first century. FAO's projections are optimistic: they see aquaculture supplying as much as 20 Mt of fish and crustaceans a year by the year 2010 after expanding by about half compared to the early 1990s. The first of the three basic modes of aquacultural production—extensive practices relying entirely on feed biomass produced naturally within the pond or other confinement—has inevitably low productivity and will make little difference to global fish supply. Yields in extensive aquaculture are as low as 100–300 kg/ha for carp raised without any fertilization, converting to no more than about 50 kg of protein per hectare.

Semi-intensive practices augment natural production of feed biomass by applying organic wastes or synthetic fertilizers and by supplementation with a variety of feeds, ranging from live invertebrates to farm-made feed mixtures and from aquatic weeds to commercially produced and nutritionally well-balanced pellets. Semi-intensive production in freshwater ponds is the world's dominant type of aquaculture.

Given China's long tradition of such practices and its continuing primacy in freshwater finfish production, it is not surprising that herbivorous and omnivorous carp now accounts for about three-quarters of the total finfish output, and that silver, common, grass, and bighead carp are by far the most abundant cultured species. Depending on the intensity of fertilization and supplementary feeding, these semi-intensive polycultures yield anywhere between 2 and 4 t/ha (up to about 700 kg/ha of protein) and the most productive ponds may yield over 5 t/ha (figure 5.8).

Intensive aquaculture produces finfish and crustaceans at high stocking densities by feeding the animals solely with commercially available or farm-prepared feeds (and in some places with locally caught low-grade fish). Carnivorous finfish (salmon, trout, yellowtail, seabream) and crustaceans (shrimps, prawns) reared in intensive monocultures within tanks, floating cages or ponds can yield over 100 t/ha. Traditional compounding of sea water containing wild shrimp spawn, and the harvesting of mature crustaceans five to six months later followed by return of the land to fields or pasture, yielded between 100 and 500 kg/ha. In contrast, two to three shrimp crops grown in ponds yield 1,000–10,000 kg of shrimp per hectare—but only by using commercial feeds.

The only case of highly intensive aquaculture not totally dependent on commercial feeds is the dike-pond culture that has evolved in parts of South China, most notably in the Zhujiang (Pearl River) Delta of

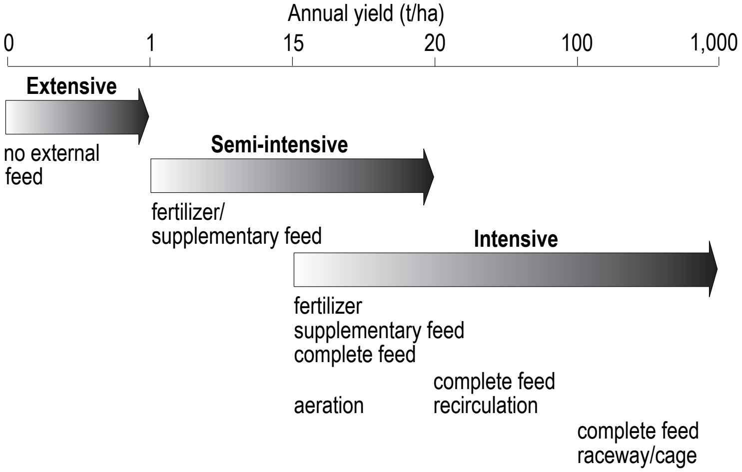

Figure 5.8
Yields and feeding options of different types of aquaculture; based on Tacon (1996).

Guangdong province, where its greatest extent reached about 800 km^2 (Ruddle and Zhong 1988; Korn 1996). This arrangement, integrating agriculture and aquaculture, is more productive than any other traditional agroecosystem. Individual units are small, just 0.2–0.5 ha; on land they comprise domestic animals (cows, pigs), intensively cultivated vegetables, sugar cane, and mulberries; in ponds they always include ducks and fish polyculture. Dike-pond units can be managed as purely organic systems, using animal wastes to fertilize crops and ponds, or they can supplement biomass recycling with externally produced feeds.

Typical annual yields are 10–15 t/ha of live fish, about 80 t/ha of vegetables or sugar cane, and 20–30 t/ha of fruits; typical annual harvests are thus between 30 and 40 t/ha of fish and crop biomass. While the management of the unit requires labor inputs equivalent to three full-time jobs, per hectare annual harvest can feed more than fifty people a year; in contrast, intensive rice farming in the same region can support no more than eleven people per hectare.

Stocking with finfish species with different feeding niches is a major reason for high aquatic productivity. Silver carp (*Hypophthalmichthys* *molitrix*) lives near the surface, feeding on phytoplankton. Omnivorous plankton-filtering bighead carp (*Aristichthys nobilis*) occupies middle water layers. Grass carp (*Ctenopharyngodon idella*) is a herbivore preferring aquatic macrophytes and feeding readily on organic wastes; the low energy content of its coarse feed makes for poor feed/meat conversion efficiency, but its feces are used, with other settled debris, by bottom dwelling detritivore and omnivore species, most often by common carp (*Cyprinus carpio*). Carp polycultures are also very efficient in using water, fit well into irrigated agroecosystems, and provide many opportunities for year-round employment.

Aquaculture's importance has grown steadily since the early 1980s to claim an increasingly larger share of the global harvest (FAO 1995a; FAO 1997). Cultured species now supply nearly 20 percent of all fishery production, with the shares of nearly two-thirds for inland production, and about 7 percent for marine output. Ocean aquaculture makes the greatest contribution in the production of molluscs—by the mid-1990s four-fifths of the world's mollusc harvest was cultured, with China, Japan, and South Korea being the largest producers—and crustaceans (with about one-fifth of all shrimp and prawns, mostly from China, Thailand, and Indonesia). And although aquaculture's contribution is still tiny as far as most ocean species are concerned, its share has now risen to over a third of the global supply for salmonids.

This recent expansion has been remarkable both because of its rate and its spatial pattern (FAO 1995a). Between 1980 and 1995 harvests of finfish, molluscs, and crustaceans nearly tripled. Since the late 1980s cultured finfish production has yielded more meat than mutton and lamb and is now equivalent to nearly a third of the world's chicken meat output (the two foodstuffs are comparable in terms of their total energy content and protein share).

Thanks to China's extraordinarily rapid growth of pond farming (from less than one Mt in 1980 to 9.4 Mt by 1995), aquacultural products are among the few foodstuffs whose production comes largely from low-income countries: in the mid-1990s about four-fifths of all finfish, and almost three-fifths of all molluscs and crustaceans, came from such countries, while affluent nations (led by the United States, France, Spain, Italy, and Norway) harvested only about one-seventh of the total mass (leaving farmed aquatic plants aside: three-quarters of them were also produced by low-income countries).

About three-fifths of cultured finfish come from inland regions, with herbivorous and omnivorous carp species accounting for more than four-fifths of all output, with carnivorous catfishes being a distant second. Carnivorous salmonids and yellowtails dominate among cultured ocean fishes. Thanks largely to rapid expansion of shrimp production, coastal aquaculture has been expanding more rapidly than inland ponds, and it now accounts for more than a quarter of total product value.

Aquaculture has several obvious nutritional and socioeconomic advantages, particularly in populous, low-income countries where—besides enriching diets with locally produced, affordable and tasty meat and high-quality protein—it can employ a relatively large number of people and be a good source of cash income. Some fish cultures can be also integrated with staple grain production: rearing fish in rice fields is a highly desirable form of agroecosystemic management that produces affordable animal protein for local consumption, provides additional labor opportunities, and boosts income of families (Choudhury 1995). Even a modest diffusion (no more than 5 percent of all paddies) and low yields (just 300 kg/ha) would produce close to 3 Mt of fish annually.

Production of nontraditional species could make a significant long-term difference. Omnivorous, mild-tasting, white-fleshed tilapia has a particularly great potential; it can be grown in warm climates in both low-intensity settings of a poor country's ponds and by intensive means in cages. Nor are the environmental benefits absent: extensive aquaculture can prevent eutrophication of waters by withdrawing suspended nutrients, and it may benefit human health by reducing certain disease vectors. But high productivities, high feeding efficiencies, and some environmental advantages are not enough to assure aquaculture's long-term future. Its practices will have to rest on a demonstrably sustainable basis, and its overall impact will have to be environmentally benign.

Problems with Aquaculture

Today's aquaculture has no greater species variety than large-scale field agriculture. About 10 percent of some 25,000 species of finfish are harvested by subsistence and commercial fisheries for food, but only some hundred species of fish—with 70 percent coming from fresh and brackish waters—are reared in aquacultures (Williams 1996). Moreover, only a handful of carp species account for nearly four-fifths of all freshwater finfish production, while salmonids provide nearly half of all carnivorous marine harvest (FAO 1995a). Narrow genetic basis is a challenge to aquaculture: the practice is dominated by a handful of freshwater herbivores and the contribution from marine species rests on even fewer carnivores. Transgenic fishes may offer many advantages by growing faster and by tolerating cooler or warmer waters (salmon with an antifreeze protein gene from the winter flounder is already available).

Availability of suitable freshwater environments, or of options for converting farmland to ponds, will be the most common constraint on expansion on land. Concerns about effects on wild aquatic species and on natural ecosystems will be a major constraint on coastal marine cultures. Environmental impacts of predatory aquaculture have become particularly common in Southeast Asia's coastal regions, and they led to a sweeping ban on virtually all commercial shrimp farming in five coastal states in India. Pollution from shrimp ponds has contaminated drinking and irrigation water, seeped into aquifers, and affected coastal fisheries (Masood 1997). Asia's shrimp aquaculture has been also responsible for destruction of mangroves and wetlands and, after the ponds are abandoned (sometimes in just five years), for creation of infertile land (Gujja and Finger-Stich 1996).

Both freshwater and marine fish farms generate pollution from the uneaten feed and fish feces made up of both suspended and dissolved organic solids, including nitrogenous and phosphorous compounds. The impact of these wastes can be particularly damaging in locations with limited water exchange where the decomposition of organic matter consumes dissolved oxygen, and nutrients contained in wastes contribute to local eutrophication, stimulate growth of bacteria and fungi, and often shift planktonic balance in favor of a few, and possibly undesirable, species. Hypoxic waters plagued by algal blooms will also affect the cultured fish, while excessive plankton can clog fish gills and its decay can produce toxins.

Deposition of uneaten feed and feces can suffocate benthic organisms and alter the chemistry of bottom sediments: The resulting anaerobic fermentation generates hydrogen sulfide, whose emanations can impair fish health and cause sudden mass mortality. The esthetic impact of manmade structures, particularly in previously untouched remote coastal regions, cannot be underestimated. Escape of the cultured species may become a more worrisome problem as aquaculture expands, especially if the transgenic organisms would be involved.

Dense stocking of most cultured species obviously promotes diffusion of pathogens; this may be aggravated by stress-induced immunosuppression. The difference between wild and farmed species is most obvious in the case of salmon: wild salmon feeds unrestrained in huge volumes of cool and clear deep-ocean waters, aquafarmed fish is confined in near-shore cages whose coastal water has higher concentrations of plankton, parasites, and pathogens. Expectedly, epizootic diseases exact considerable toll. Estimates from China's Jiangsu province indicate that losses to diseases amount to at least 20 percent of total annual finfish production, to as much as 40 percent of shrimp, and 50 percent of mollusc output (FAO 1995a). During the early 1990s epizootics caused a collapse of shrimp farming in China, a more than 70 percent reduction of total output between 1991 (when the country was the world's largest producer) and 1994.

Chemicals used to prevent and limit these diseases naturally contribute to selection for more resistant strains of bacteria and may contaminate the edible product as well as sediments and other aquatic species. Controls of serious epizootics by antibiotics or other chemicals may also pollute confined waters; leave residues in the fish, in wild organisms, and in other farm products; and help to develop drug-resistant pathogens. As a result, consumer acceptance of aquacultural products may decline. Some of these concerns are relatively easy to address; others will persist. Feeding waste can be much reduced by using highly digestible compounds dispensed at rates maximizing intake. Waste recycling is practical in intensive tank cultures as is the effective waste removal (sedimentation, filtering) in flow-through arrangements—but difficult or very costly in larger ponds and lagoons and from beneath submersed cages.

Securing appropriate feed for carnivorous species will be an increasing challenge. While in some carnivorous fishes (catfish and eels) protein digestibility differs little among high-quality feeds of animal and plant origin, other species, including rainbow trout and salmon, prefer feeds of animal origin to meals derived from soybean or cottonseed (Steffens 1989). Moreover, fish meal and fish oil are the only available source of highly unsaturated fatty acids that are both essential nutrients for all carnivorous finfish and a key reason for health appeal of these foods. These high-protein and high-fat feeds are often derived from marine products: fish meals and fish oils usually make up about 70 percent of feeds for carnivorous finfish and (supplemented by shrimp and squid meals) about half for crustaceans (Chamberlain 1993).

All carnivorous finfish and shrimp species reared in an semi-intensive and intensive manner are thus net protein consumers rather than producers: depending on the arrangements and particular feeds, their needs for fish proteins exceed their protein output two to five times (Tacon 1995). And the culturing of carnivorous species contributes to depletion of marine stocks: the rapid expansion of Thai shrimp farming was made possible by inexpensive fish meal supplied by the trawl fishery in the Gulf of Thailand.

Aquaculture is still an insignificant consumer of commercial animal feeds, but its use of fish-derived feeds is already substantial, accounting for some 15 percent of all fish meals and fish oils in 1995 (Tacon 1994). Most of these fish-derived feeds are still used in chicken and pig production, but the rising output of carnivorous finfish (now accounting for about one-eighth of all farmed fish) would increase the share of high-quality feeds. Although it is unlikely that shortages of fish meal and fish oil will restrict aquaculture in short or even medium term, the use of fish biomass in fish production obviously represents a long-term limit on the output of carnivorous species. Rising feed prices may eventually limit the use of fish-derived feeds and crustaceans, and mesopelagic fish may be used for feed.

Affluent countries can afford carnivorous aquaculture. Japan's output is dominated by carnivorous yellowtail, seabream, and eel. In contrast, in China, the world's leading aquacultural power, about 98 percent of

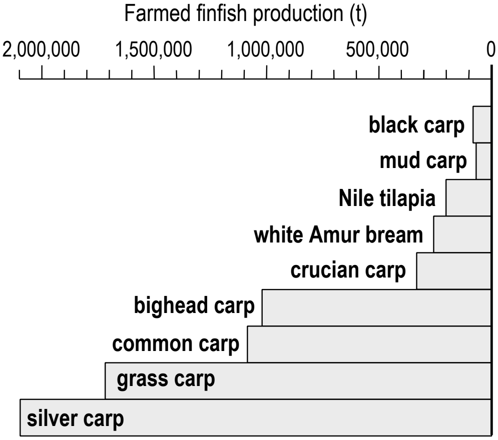

Figure 5.9
China's aquacultural finfish production of the mid-1990s was dominated by herbivorous species; the most important fish, silver carp, contributed about 2 Mt/year. Based on Tacon (1996).

cultured species are herbivores and omnivores (figure 5.9). If aquaculture is to make substantial long-term nutritional difference on the global level, then energetic imperatives will favor the production of herbivorous and omnivorous species.