A Fair Share: Doing the Math on Individual Consumption and Global Warming

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Chapter 21

Animal products and livestock

As already discussed in the introductory chapter to this part of the book, animal agriculture, which entails the processing of grain and forage inputs at a marked energy and mineral nutrient loss to animal outputs, dominates the environmental footprint of agriculture, including its global warming impact. In addition to the feed conversion efficiency issue, methane from enteric fermentation in ruminants (cows, sheep, and goats) and both methane and nitrous oxide from manure management are major greenhouse gas sources. Furthermore, land degradation and land-use change also lead to carbon emissions. Not all animal products, however, are created equal, with beef (and other ruminant meat such as sheep and goat) qualitatively far worse than all other major animal products: while accounting for less than 4% of the American diet (on both a weight and energy basis), beef is responsible for 30–35% of the dietary greenhouse gas impact (and a *majority* of the land-use impact). An iso-caloric shift to any other major non-ruminant meat animal product (dairy, poultry, pork, or egg) would result a 75–90% reduction in GHGs, while a shift to any plant source of protein would likely reduce emissions by >90%. Dairy, poultry, pork, and eggs are all relatively similar in their GHG impact, although dairy is the worst when measured on a $kgCO_2e$ per protein basis, with poultry and eggs the best.

Overall, animal products together probably account for as much as 70–75% of the greenhouse gas impact (and broader environmental impact) of American diets. Vegetarian diets are likely about 30–35% less emitting than omnivorous, while vegan diets may be as much as 50% less emitting. Again, a majority of the climate benefit to a vegetarian diet stems from eliminating beef in particular, rather than meat in general. One need not abstain completely, as low meat diets are much more benign than either typical or high meat diets; limiting, even if not eliminating, dairy is also quite beneficial. I also believe that the somewhat all-or-nothing mental model of complete abstinence (vegetarian or vegan) versus "anything goes" can be unhelpful, and it bears emphasizing that (meaningful) harm *reduction*, not harm elimination (which is impossible) or moral purity should be our primary goal.

It should further be noted that while vegetarian diets are generally superior to non-vegetarian, when these diets substitute large amounts of dairy for meat this is not necessarily a boon, as dairy systems are relatively high carbon, have many associated animal welfare issues, and in fact supply a nontrivial fraction of meat to the beef system. Therefore, the omnivorous/vegetarian dichotomy is not necessarily the best diet distinction, and some meat products, e.g. chicken, are as good or better than dairy, at least on a global warming (and land-use) basis. A vegetarian diet that substituted dairy for all meat would be similar to and possibly worse than an omnivorous diet that simply cut out beef.

The goals of the remainder of this chapter are to review, in detail, some of the major US animal production systems (especially beef and dairy), their greenhouse gas impacts—both magnitude and mechanism (to wit, enteric fermentation, manure management, and feed production)—and some associated controversies, including the effect of grazing systems on soil carbon stores.

21.1 Major prior assessments

Two major reports are frequently cited in the popular media, and it is worth reviewing both. The first, "Livestock's long shadow" by the FAO, is a masterful work that reveals the gravity of the problem, while the second, a Worldwatch Institute report, is perhaps well-meaning, but profoundly exaggerates the impact of livestock and is an example of results-driven research that must be rejected.

21.1.1 Livestock's long shadow: The FAO report

In 2006, the Food and Agriculture Organization (FAO) of the United Nations published a report entitled "Livestock's long shadow" [389]. The report stated in no uncertain terms that the global livestock sector is one of the top contributors to almost every serious environmental problem, including land change and degradation, loss of biodiversity, water use and pollution, and global climate change. The report estimated that livestock accounts for 18% of global greenhouse gas emissions overall, and in particular, livestock were estimated to be responsible for 9% of CO_2, 34% of all methane emissions, mainly from enteric fermentation, and 65% of nitrous oxide emissions, largely from manure.

Tilling of arable lands to grow animal feed, deforestation for pasture, and rangeland degradation from overgrazing are all also significant sources of carbon emissions. Indeed, the report related that, on a global scale, livestock grazing uses 26% of the earth's ice-free land, 33% of cropland goes towards producing animal feed, and in sum, 70% of agricultural land and about 30% of *all* land goes towards raising livestock. Note that these are global figures, and in the US the situation is even worse, with closer to 50% of the nation's entire landbase directly or indirectly devoted to livestock. Conversion of Amazonian forest to pasture and feedcrop production (e.g. soybeans) is the major driver of rain forest deforestation, and a significant portion of grazing lands have been degraded by overgrazing. These vast tracts of agricultural land were once wildlife habitat. This, combined with the depletion and pollution of water sources and the stressing effect of climate change, imply that agriculture, especially livestock, is the greatest global threat to biodiversity. Thus, the environmental impact of livestock extends far beyond carbon emissions alone.

21.1.2 Worldwatch report: 51%? An implausible estimate.

While the FAO gave 18% as their estimate of the global warming share attributable to agriculture, a widely cited report by the Worldwatch Institute, published essentially as a response to *Livestock's long shadow*, claimed that livestock alone (not even including the remainder of the agricultural system) accounts for a staggering 51% of all anthropogenic carbon emissions. Note that this calculation is derived *after* the authors claim that existing inventories undercount emissions by 25.0 $GtCO_2e$ per year (all additional emissions attributable—supposedly—to livestock), raising the cited global total emissions from 41.8 $GtCO_2e$ to 66.8 $GtCO_2e$. That is, the authors assert that the FAO accounting was almost fivefold too low (as the FAO 18% figure adjusts to 11.8% of emissions under the new grand total), and that existing carbon inventories have ignored almost 40% of all emissions. This claim approaches absurdity almost *prima facie*, and a closer look validates my skepticism. Some of the errors are worth examining in detail.

Respiration is not a carbon source

The most obvious error, and it is *unambiguously* an error, is the claim that livestock respiration counts as an anthropogenic carbon source, to the tune of 8.8 $GtCO_2$/yr (the largest "correction" to the FAO figure, and more than the US's entire annual emissions). Respiration is the conversion of food energy to CO_2 and H_2O, and (nearly) every living thing does this. Respiration by any animal, including humans, that does not act on some long-term carbon store is *never* counted as an anthropogenic emission: it is a natural background process that entails rapid cycling between carbon pools, and does not add to long-term CO_2 atmospheric concentrations. It does not matter if the cows are a creation of Man, or that they are consuming food grown on deforested land with an attendant carbon debt. It is correct to account for the carbon debt incurred when one switches to a forest system to a cropping system, but one cannot count the carbon from metabolizing food grown on the cropping system.

It is an important point that respiration generally should not be counted towards emissions totals, as it occasionally is in various contexts. I recall a GOP politician once claiming that bike lanes are bad because cyclists emit CO_2 when exercising. While the objection is obvious nonsense at any level, it also fails to appreciate that respiration, even by humans, should not be counted as an anthropogenic emission at all. The major exception is when long-term carbon stocks (e.g. soil carbon, peatland) are altered by human intervention such that they are oxidized to CO_2 via respiration, and thus yield *new* atmospheric CO_2. By the same token, CH_4 produced via enteric fermentation is *new* to the atmospheric system in a way that oxidized crops are not, and is thus tabulated as a new emission.

Other claims

Of other dubious claims, the most important is that the "appropriate" time-frame for methane GWP is 20 years, not 100, and using 20 years inflates the effect of methane from livestock approximately threefold compared to FAO estimates. Indeed, it is not at all obvious what the proper time-horizon for evaluating global warming potentials is, and there is no general method to decide what is appropriate, but the international standard has been 100 years, and in any case, all other greenhouse gases must be recalibrated to 20 year GWPs for a consistent inventory.

Some of the other claims are not necessarily unreasonable. For example, land-use changes are posited to be undercounted by the FAO, as the use of agricultural land is not compared against a counterfactual of either abandonment or cultivation of food for direct human consumption or biofuels. Additionally, increases in livestock head compared to the time FAO statistics were compiled would imply increased emissions. Finally, meat cooking, waste disposal, livestock-related infrastructure, animal-borne illnesses, and several other more indirect activities are claimed to account for 13% of global carbon emissions (5.6 $GtCO_2e$, close to the US's annual emissions from all sectors). This latter sum also strikes me as implausible on its face, but I will not take the time to thoroughly dispute it. The inclusion of respiration alone as a carbon source discredits any conclusions, and it strikes me as a fine example of results-driven research. We must reject all such work, even if it is well-meaning and seeks to address a real problem of global significance, in favor of a clear and honest assessment, regardless of what conclusions it should leads us to.

21.2 Beef and other ruminant meat production

It is universally accepted in the scientific literature that beef production has the highest overall and per-unit environmental impact of any large-scale agricultural activity, being both extremely emissions-intensive and land-intensive per kg of production (see, e.g. [322, 457, 390, 467]). Cows are ruminants, a class of animals that includes a variety of hoofed mammals, and that are unique in possessing a four-compartment stomach wherein coarse plant matter is broken down by symbiotic microbes via *enteric fermentation*, a process that releases methane and is thus largely responsible for the high global warming impact of cattle production. Ruminants' major evolutionary advantage is the ability to digest cellulose via fermentation, a feat many animals are incapable of. In addition to methane release, ruminants also very inefficiently convert feed into growth compared to monogastrics (i.e. single-stomached animals, including humans, pigs, and chickens) [322], and thus both grass- and grain-fed ruminants are associated with excessive embodied emissions, fertilizer, pesticide, water, and land-use.

It follows that, compared to most other animal production or direct consumption of crops (vs. feeding them to animals), large-scale cattle and other ruminant, e.g. goat or lamb, production is intrinsically more harmful, thanks to enteric fermentation and feed conversion inefficiency. This applies not only to conventionally produced beef, which are "grain-finished" in feedlots, but to purely grass-fed beef as well. Indeed, the relative impact of grass-fed vs. conventional (grain-finished) beef is a recent controversy, but the literature does seem to support the conclusion that grain-fed beef actually has a lower carbon footprint and requires less land to produce [439, 407]. This is true for two basic reasons: (1) grain fattens cows up more efficiently, and (2) less methane is released per unit of grain than per unit grass.

The perhaps disturbing conclusion is that simply purchasing grass-fed beef in lieu of standard fare is no solution at all: if we demanded the same level of beef in our diets as we have now, then converting to an all grass-fed system would in fact generate more carbon emissions, use and degrade more land, and be wholly unsustainable. The proper solution then must simply to reduce consumption of what is properly understood as an intrinsically harmful luxury product, but that may be acceptable as a *small* part of a larger system.

21.2.1 Survey of LCAs

- Lifecycle analyses suggest carbon emissions on the order of 30–50 kgCO_2e/kg boneless beef, for meat produced in American beef-only herds, with higher figures, e.g. 40–50 kgCO_2e/kg boneless beef more consistent with top-down estimates of livestock methane emissions.
- More intensive management systems generally have lower CO_2e and land requirements per kg of beef; lifecycle emissions for grass-finished beef are probably 15–30% higher than for conventional systems.

Lifecycle analyses have generally reported carbon emissions on the order of 20–50 kgCO_2e/kg of beef, for the US, Canada, and other Western Countries (Canadian and US production systems are fairly similar). For example, 15 estimates compiled by Desjardins et al. [407] for mainly US, Canadian, and Western European conventional beef systems averaged to around 30–35 kgCO_2e/kg beef (converted from about 12–14 kgCO_2e/kg live weight), although these studies varied significantly in how they accounted for carbon sequestration or loss from land-use change and land-management, the interaction with the dairy system, the role of co-products (e.g. leather hides), and overall system boundaries. However, other estimates are closer to 50 kgCO_2e/kg beef [439, 388]. Analyses have also fairly consistently concluded that "grass-fed" (a term that, in popular use, really refers to "grass-finished," as explains below) actually have higher greenhouse gas emissions than conventional systems [439, 392].

Globally, emissions estimates from life-cycle analyses have ranged from 9–129 kgCO_2e/kg beef, with more intensive production systems generally lower in their carbon impact [390].

Desjardins [407] and colleagues have suggested that carbon emissions are likely lowest in the West, where production systems are much more efficient than those in the developing world and indeed, analysis by the FAO [388] suggested that more industrialized North American beef is less than half as emissions-intensive as that in sub-Saharan Africa and several other developing areas. Along these lines, Capper et al. [391] concluded that with increased efficiency, the carbon footprint of beef in the US decreased by 16% from 1977 to 2007. Note also that, since the methane GWP potential estimates have been recently revised upwards, most existing analyses likely underestimate CO_2e emissions by 12–17% (calculated assuming 40% of lifecycle emissions are from methane, and correcting with a 34 to 21 or 25 ratio).

Before continuing, it is important to note that the functional unit of analysis in studies varies between carbon footprint per live weight (LW), carcass weight (CW), and boneless meat. Live weight is obvious, whereas carcass weight is the weight following slaughter and removal of the head, hide, feet, and viscera, and is only about 50–65% of live weight [407, 408]. Further, only 55-75% of the carcass weight ultimately yields boneless, trimmed retail cuts of meat [408]. Therefore, generally speaking only about 40% of an animal's live weight ends up as retail meat. Thus, if one estimated, for example, 20 kgCO_2e/kg live weight, this should translate into about 50 kgCO_2e/kg retail boneless beef.

Multiple studies have examined the emissions from model herd systems. Indeed, we must understand that the beef cattle system entails a whole herd with several different roles. Only a fraction of cows are brought to slaughter each year, but we must sum the emissions from the entire herd system to get a valid per product emissions factor. Further complicating the matter is the fact that dairy and beef herds are interconnected, making emissions allocations trickier. I discuss correcting for the dairy system in Section 21.4.3, but for now, let us examine isolated beef production, which is the dominant model in the US. Worldwide, a slight majority of beef actually comes from the dairy system, in the form of fatted calves and culled milk cows [432].

A prototypical beef-only herd consists of cow/calf, stocker, and feedlot components [439]. In the cow/calf herd, there are, say, 100 mother cows who give birth each year with a success rate of about 90%, along with 15 heifers (young female cows that have yet to give birth), and perhaps three bulls for breeding (alternatively, artificial insemination may be used), one of which is culled yearly. The mother/calf pairs (and heifers) graze on pasture or range, with the calf fed on its mother's milk until weaning at about six months of age. Shortly after weaning, the calf undergoes one of several fates. First, perhaps 15 female calves are kept in the cowherd as replacement heifers, to ultimately replace 15 older cows that are culled (i.e. sent to slaughter for beef). Note that this implies mother cows last about seven years, on average, before culling.

Now, the remaining calves (both male and female), are used for beef. Some fraction is sent to a stocker system ("yearling" system), which entails a further 6–10 months of grazing (also called backgrounding), and then to a feedlot for "finishing" on a high-grain diet (additional 6 months). Thus, these calves take about 450 days beyond weaning to reach slaughter. The other calves are sent directly to feedlot ("weanling" system), where they finish in about 300 days [439]. A tiny minority (<1%) of calves are finished on pasture instead of feedlot. This is what labels such as "100% grass-fed" or "grass-finished" refer to: all beef cattle spend the first portion of their life grass-fed. At every stage of this process there are direct emissions, primarily CH_4 from enteric fermentation and N_2O from manure, along with indirect emissions from feed production; the process is illustrated in Figure 21.1. Note that even during the grass-fed stages, cattle require significant outside inputs in the form of hay (especially over winter) and other supplemental feed (e.g. oilseed cakes) grown on arable land.

A fairly comprehensive analysis by Pelletier and colleagues [439] compared stocker/feedlot, feedlot-only, and pasture finishing systems for Upper Midwestern beef production systems. This system is geographically notable in that the pasture systems are intensively managed, i.e.

fertilized, seeded, etc., as opposed to unimproved rangeland, stocker cattle are maintained on wheat fields, and a significant portion of the forage fed to pastured cows is, in fact, alfalfa hay that is grown on cropland (although this is common). Thus these pasture systems are more energy intensive than in many parts of the US. At any rate, including emissions from enteric fermentation, manure, and feed production, we arrive at about 40, 37, and 47 kgCO_2e/kg beef for the stocker/feedlot, feedlot-only, and pasture systems, respectively. Note that the pasture finishing system also required 25–50% more land than the conventional systems. By far, most emissions are generated by maintaining the cows and heifers in the cow/calf system.

I have done my own calculations using Pelletier et al.'s figures on feed, fertilizer and fuel inputs for feed production and have obtained (also using updated CH_4 GWP values) about 20 kgCO_2e/kg boneless beef attributable to enteric fermentation in the two conventional systems, and 27 kgCO_2e/kg in the pasture-finished system. Pelletier et al.'s analysis also indicated 9–10 kgCO_2e/kg from manure management in the conventional systems, and about 10 kgCO_2e/kg in the pasture system, with almost all this due to N_2O. Adding in upstream feed production adds about 10–15 kgCO_2e/kg beef, and thus, we sum to about 40–45 kgCO_2e/kg for conventional beef, and 45–50 kgCO_2e/kg for grass-finished.

Numerous other studies (e.g. [392, 393, 390, 388]) have been published in the last few years with all coming to essentially the same conclusions, and while there is some variation in exact emissions estimates, there is no real disagreement concerning the order of magnitude of beef's impact.

21.2.2 Carbon sequestration from grazing?

A central issue in lifecycle analysis for the overall impact of beef (and dairy) in general, and in determining the comparative impact of grass- and grain-finished beef, is how grazing and other land management strategies affect grassland (and other rangeland biome) carbon stores. Overgrazing can lead to land degradation and desertification, characterized by a shift in dominant vegetation and loss of soil organic carbon. This is especially true in the more arid areas of the world [389]. On the other hand, well-managed grazing may beneficially affect vegetation and increase soil carbon, mainly in biomes that were subject to grazing by large generalist herbivores during their evolutionary history. It is sometimes claimed that, because of such carbon sequestration, grass-fed beef has a lower, nil, or even negative greenhouse gas impact.

Despite decades of work, overall conclusions on the effect of grazing on SOC stocks are unclear, with studies variously showing a positive, neutral, or negative effect; it is doubtful that grazing has a globally uniform effect, implying that grazing strategies must be tailored, at the least, to grassland biome. Conclusions drawn from studies of the American Great Plains, for example, which historically evolved under grazing pressure from large bison herds, are not generalizable to the more arid lands of the far American West and Southwest, which evolved largely in the absence of such pressures. It clear that climate, precipitation, soil type, and vegetation type interact to determine carbon sequestration and the net effect of grazing. In any case, grazing is *not* a dominant factor in determining soil carbon, except when it induces desertification, with rainfall and climate far more important.

Great Plains

Let us first focus primarily on studies of the Great Plains region which, again, was subject to heavy bison grazing in recent evolutionary history (although it should be noted that the exact size of historical bison herds is remarkably uncertain, with widely cited estimates based upon almost nothing, and it can only be stated with any certainty that at least several million and possibly several ten million bison once roamed the Great Plains, as reviewed by Shaw

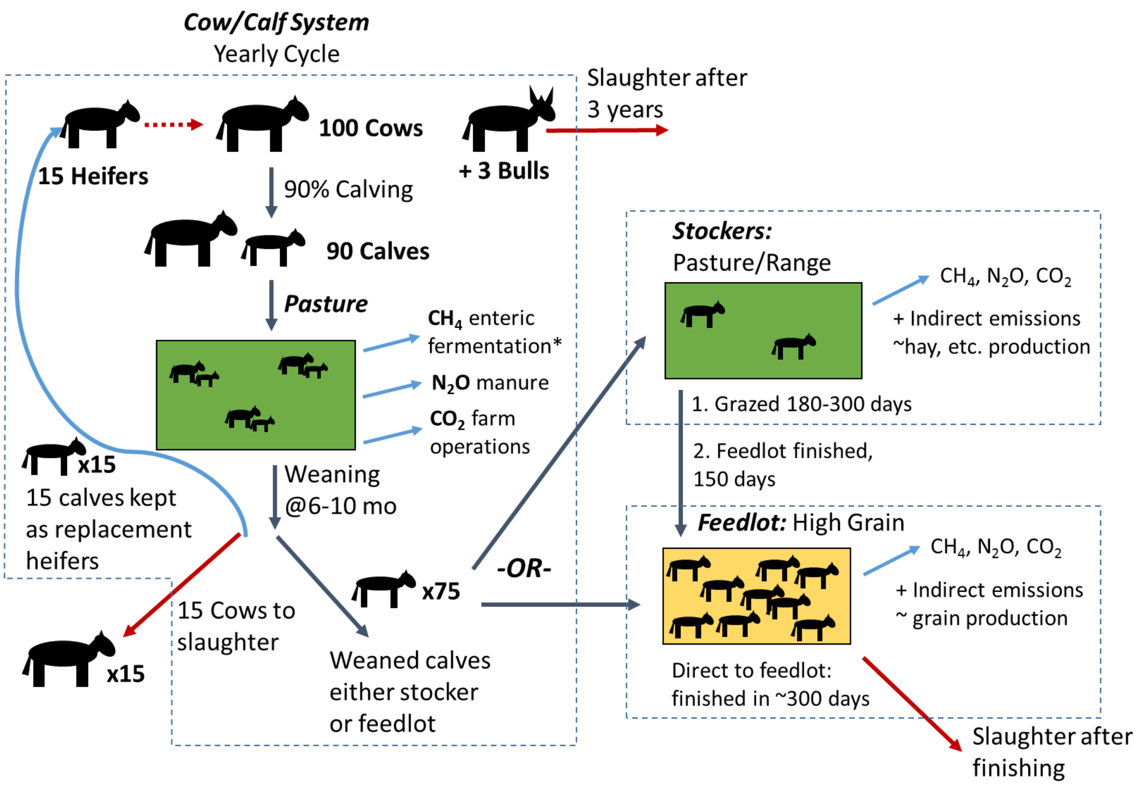

Figure 21.1: Schematic for the beef-only production system that dominates in the US. At the first stage, we have cow/calf systems where out of 100 cows, perhaps 90 will calve each year. These calves are kept with their mothers on pasture until weaning, at which point they are sent either to a stocker (or "backgrounding") system where they continue to graze for 6–10 months before feedlot finishing, or older calves may go directly to feedlot. Note that about one in seven cows are culled yearly, and so 15 heifers are retained. Most emissions in the beef system are attributable to the cow/calf stage.

[394]). This region is characterized by a general increase in precipitation from west to east, with a corresponding shift in grassland type from shortgrass to mixed-grass (or "midgrass") to tallgrass prairie. As one moves west to east the productivity of the land increases, the soil carbon stores increase markedly, and the root:shoot grass ratio decreases (i.e. there is comparatively more above-ground than root biomass) [397, 396]. These factors all shift in proportion to the precipitation level [397, 398]. It makes sense that grasses in the less productive, drier west devote more mass and energy to their root system (higher root:shoot ratio), the better to acquire water and avoid transevaporation. With less carbon input from plant growth and decay, it is also logical that soil carbon stores are much lower in the drier west.

Now, it has been fairly consistently found that annual precipitation determines not only prairie composition, but also (at least indirectly) carbon sequestration in response to grazing, with *lower* average precipitation predicting increased SOC under grazing, while higher precipitation may actually lead to decreased SOC under grazing. Derner and Schuman [396], reviewing Great Plains studies, observed the SOC grazing effect to shift from positive to negative at about 440 and 600 mm of precipitation for the 0–10 cm and 0–30 cm soil horizons, respectively. Note, however, that *drought* (i.e. a negative departure from average precipitation levels) may conversely interact with grazing to *reduce* SOC [399].

Short-term carbon sequestration in grazed versus ungrazed patches has been measured on the order of 0.07–0.12 MgC Ha^{-1} yr^{-1} in shortgrass prairie, and around 0.3–0.4 MgC Ha^{-1} yr^{-1} in mixed-grass prairie ([396, 401]); the effect may be negative in tallgrass prairie as well as in some mixed-grass prairies [397]. While sequestration has been observed over multiple decades, e.g. [401], *overall*, the influence of grazing on soil carbon stores tends not to increase, as might be expected if additional carbon is stored every year, but to *diminish* in longer-term trials [395, 396, 399] (see, e.g., Figure 3 of [395], where effect size, either positive or negative, clearly diminishes with trial length, or Figure 1 of [396]). Given that, with time, the difference in soil carbon between grazing treatments tends to regress towards zero, it is clear that any grazing-induced SOC increases will not continue indefinitely, and that at best grazing induces a (likely small) shift toward a new steady-state SOC level. I discuss the likely mechanism for this pattern below. These general patterns are shown in Figure 21.2.

In general, grazing increases nutrient *cycling* in a prairie system, reduces the carbon stored in above-ground plant matter (as it is being eaten), may or may not reduce root biomass, and can shift carbon into the soil with a net increase in total ecosystem carbon, but a soil carbon loss is also possible. To get a clearer theoretical understanding of these disparate grazing effects, it is worth taking a closer look at one study, by Derner et al. [397] on the effect of grazing on shortgrass, midgrass, and tallgrass grasslands in the US Great Plains. In this study, all prairie types saw a reduction in above-ground biomass, but while root mass in the midgrass and tallgrass biomes was reduced, it was stable in the shortgrass system; although root mass was stable, root *distribution* was not. This is because the essential effect of grazing in shortgrass system was to reduce *C3 grasses* in favor of *C4 grasses*, particularly the C4 grass "blue grama" (*Bouteloua gracilis*). This C4 grass is characterized by a fine root system concentrated in shallower soil (83% of root mass in the first 0–15 cm [399]), contra the root systems of C3 grasses, which tend to be deeper and coarser (more uniform distribution up to 60–90 cm deep).

Before continuing, I should briefly clarify that grasses are broadly divided into C3 and C4 types, with the two having different photosynthetic pathways. The C3 grasses are "cool season" grasses, adapted to wetter and colder environs, while "warm season" C4 grasses are better adapted to hotter, drier conditions.

Now, we have that grazing, likely through preferential consumption, can cause a shift in grass type from C3 to C4, potentially causing an overall drop in root biomass, but shifting the bulk of the roots into shallower soil, and thus more root carbon is brought near the surface.

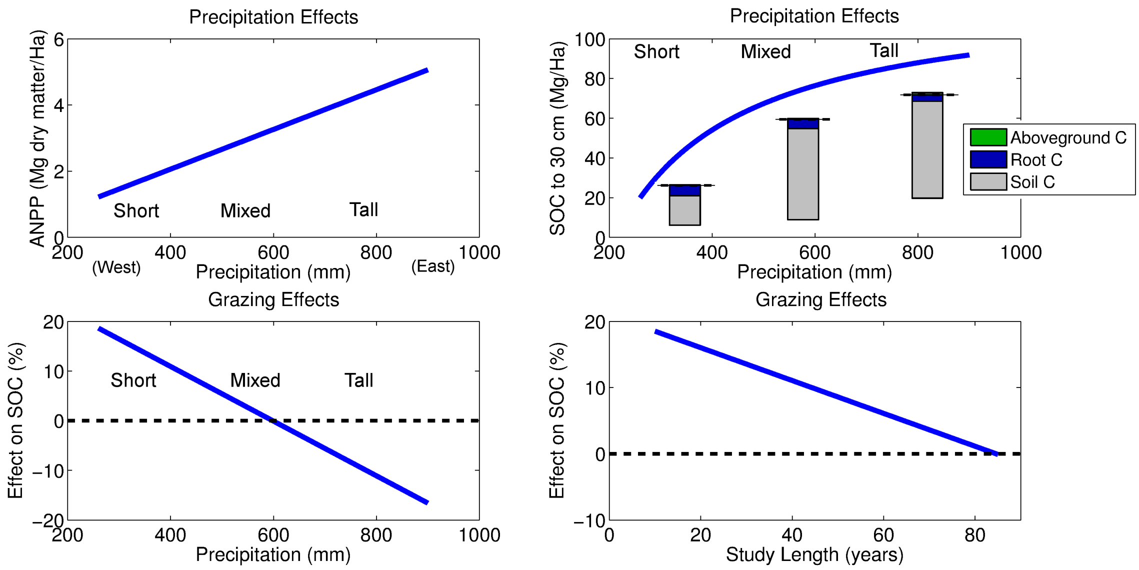

Figure 21.2: General trends in precipitation and grazing effects on the Great Plains. The top left shows how above-ground net primary productivity (ANPP) increases linearly with precipitation as one moves geographically west to east, and through shortgrass, mixed-grass, and tallgrass prairie types (data from [398]). The top right shows the hyperbolic increase in SOC with precipitation, again over this west-to-east gradient (SOC curve adapted from [396]). Inscribed is the distribution of ecosystem carbon for example (ungrazed) shortgrass, mixed-grass, and tallgrass prairie sites (from [397]), and we see that absolute carbon stores increase from west to east, while root mass decreases. Above-ground biomass is barely perceptible, but also increases west to east. The bottom panels show (left) that grazing may have a positive impact on SOC in drier western shortgrass and (possible) mixed-grass prairie, but generally shifts to a negative effect in the wetter east, while the absolute impact (positive or negative) tends to diminish towards zero (right panel) with study duration, implying that any short-term effect is generally not sustained.

In addition to this vertical carbon shift, C4 grasses also innately devote more photosynthate to the roots, and root matter nearer the surface decays faster than deeper roots [396, 399]. Thus we can see an overall increase in carbon entering the soil, with the increase concentrated in the upper horizon. With heavy grazing, this C3 to C4 shift may occur faster [399]. High precipitation, relative to the biome average, will lead to more overall plant growth and more carbon entering the soil as a consequence, and thus heavy rains and heavy grazing may synergize to store carbon beyond either light or no grazing. I say high precipitation *relative* to biome average because this cascade seems mainly to occur in the semi-arid shortgrass biome.

On the other hand, if grazing reduces overall plant biomass (especially below-ground) without a change in the vertical root distribution (or possibly even with such a change) then ultimately less carbon enters the soil as decaying plant matter, and SOC stocks will decrease. In this case, heavy grazing will reduce SOC stocks more than light grazing. This is what appeared to occur in mixed-grass and longgrass prairie studied by Derner et al. [397]. In these systems, the grass was predominantly C4 even without grazing, and no C3 to C4 shift occurred with it. Note that these two prairies are much wetter than the shortgrass system, with much higher baseline soil SOC, and it may also be that increased nutrient cycling under grazing leads to excessive microbial oxidation of soil carbon when water is more available for microbe metabolism.

Finally, heavy grazing in shortgrass or mixed-grass biomes that has a short-term carbon storage effect may set the system up for greater carbon losses later when the system is perturbed by drought. This would explain why little long-term grazing effect is seen, and is precisely what was observed by Ingram et al. [399] who reported marked SOC accumulation in heavily grazed (50% forage utilization) mixed-grass prairie after 12 relatively wet years (see also [400]), but even greater SOC losses in the subsequent drier decade. At the last count, the heavily grazed fields were lowest in soil carbon and above-ground biomass, while the lightly grazed fields (10% forage utilization) were healthiest [399].

These effects of grazing are illustrated in Figure 21.3. We may conclude that, in general, light grazing is probably sustainable throughout grasslands that evolved under large herbivore grazing pressure, with little change in range productivity and possibly small increases in soil carbon in the western Great Plains. While certain grasslands may experience large short-term soil carbon gain with heavy grazing, this reduces range productivity [399, 422], is unlikely to be sustained long-term in most cases, and is most likely ultimately counterproductive. The C3 to C4 grass shift is likely the major mechanism for increased SOC under grazing, and this tends not to occur in more easterly, wetter prairies. Climatic factors, mainly precipitation, are clearly far more important than grazing in determining SOC (for example, Derner and Schuman [396] found precipitation to explain 83% of the SOC variance across the Great Plains), except when severe overgrazing degrades the land.

Grazing in the far American West: carbon loss and widespread ecological damage

- Much cattle ranching occurs west of the Great Plains, where it almost certainly causes widespread ecologic harm and dramatically reduces soil carbon stores.
- Widespread predator and wild herbivore suppression and eradication is another ongoing consequence of livestock ranching.

The biogeography of the far American West, and particularly the American Southwest, is distinct from that of the Great Plains. These arid and semi-arid lands are characterized by low vegetation cover, low levels of soil organic matter, vulnerability to erosion, and very low grazing

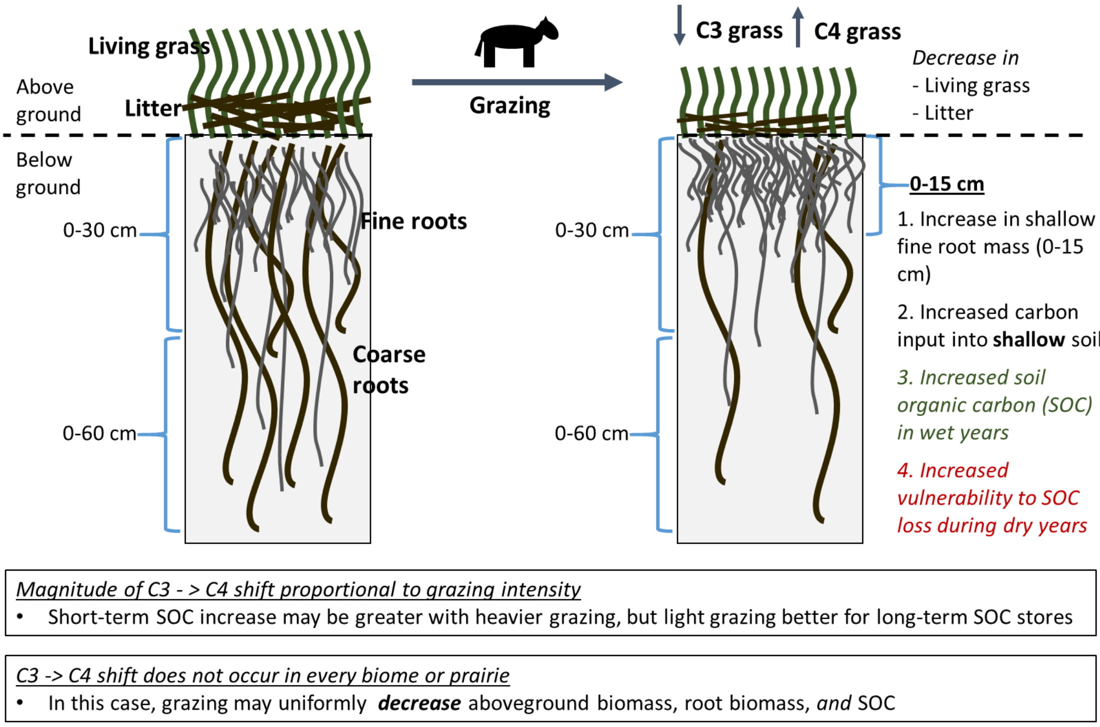

Figure 21.3: Schematic for how grazing might increase SOC via a shift in C3 to C4 grass species, mainly blue grama (*B. gracilis*), and a corresponding shift of root biomass to shallow fine roots. Note that this shift does not occur in all biomes, e.g. tallgrass prairie and some mixed-grass prairie, and in such cases grazing probably has a negative effect on SOC regardless. In shortgrass biomes where this shift does occur, heavy grazing can make the shallow SOC vulnerable to erosion and loss during drought years, and thus may be counterproductive overall. Light grazing may sustain small increases in SOC longer-term.

pressures in their evolutionary history [419]. Thus, grazing by human-imposed large herbivores can severely degrade these lands. For example, Neff et al. [402] compared a never-grazed site in the Canyonlands National Park of southeastern Utah to two very similar sites grazed from the 1880s through 1974, and found, even 30 years following grazing cessation, markedly reduced mineral nutrients, SOC (40–70% lower), and soil nitrogen (40–85% lower) in the grazed sites. This was likely attributable to a combination of increased decomposition of carbon in disturbed soils, increased wind erosion, changes in vegetation, and destruction of biological soil crusts, which stabilize soil and fix nitrogen.

Indeed, livestock use of largely public land in the American West is generally understood to be an ecological disaster [403]. While land and ecologies in the American West have been dramatically affected by numerous human activities, including widespread fire suppression, large-scale re-engineering of the region's hydrology (e.g. massive damming and canal projets), logging, and near-eradication of large apex predators, the widespread introduction of non-native grazing animals is perhaps greatest in the scale of effects, and there is very little wild land remaining in the West never subjected to grazing [403].

With global climate change, temperatures in the American West are increasing, and the region is becoming increasingly vulnerable to drought, and thus also increasing soil vulnerability to livestock, which may increase erosion via several mechanisms. As mentioned above, introduced livestock trample biological soil crusts, which stabilize soil and can take centuries to fully regenerate. Trampling also compacts soil and decreases water infiltration, causing increased runoff and erosion.

Feral horses and burros, living primarily on BLM land, also have deleterious ecological effects. Native wild ungulates can cause problems as well, mainly because human control and eradication programs of large predators have disrupted the basic predator-prey ecology [403]. Indeed, suppression of wild animals, both predator and prey, is also a grievous byproduct of livestock ranching. As the Midwest and West were settled by European-descended families, large prey such as bison and elk were nearly eradicated by over-hunting. As their former predators increasingly turned to introduced domestic livestock for sustenance, the US government carried out multiple predator eradication campaigns. Furthermore, multiple extermination campaigns were waged against native herbivores perceived as competitors to livestock, none so much as the beleaguered prairie dog. These campaigns are not merely historical, but continue to this day: In 2014 Bergstrom et al. [404] documented that Wildlife Services, an agency of the USDA, since the year 2000 directly killed (either intentionally or unintentionally, e.g. via indiscriminate trapping) two million native mammals and 15 million native birds. Moreover, these campaigns were largely unscientific and often ineffective or even counterproductive at achieving even their stated goals. These culls largely stem from a desire to promote domestic livestock herding (and to promote certain game species hunted by humans).

Global desertification

Desertification, the conversion of arid grassland to desert shrubland, has been estimated to affect a full 25% of the world's land, and is primarily driven by overgrazing and drought, with the former likely the more important factor [405]. While traditionally viewed as an irreversible process, there is evidence that, with the removal of livestock, desertified lands may slowly recover [405]. Given the magnitude of the problem, and the clear role of livestock grazing, it seems obvious that grazing is clearly deleterious to soils on a global scale.

21.3 Alternative grazing systems and meat sustainability

I would argue strongly that red meat must be considered a luxury, as its production requires vast amounts of land, directly generates a substantial portion of all greenhouse gases, is the leading cause of rangeland degradation and desertification, and is also a major global driver of deforestation. However, the idea has recently come into vogue that this is all a consequence of altering natural herbivore-grassland interactions and that, when *properly* managed, cattle grazing, at even higher intensities than currently done, can not only restore the earth's rangelands to their former vigor, but could actually sequester *all* anthropogenic carbon emissions. This idea was rather famously popularized in a 2013 TED Talk by Allan Savory, who promotes so-called holistic management (HM), also known as short-duration grazing or intensive rotational grazing (IRG). Some of the major claims follow [420]: (1) all grasslands evolved in the presence of large herbivores that grouped into large herds, due to predation, (2) such herds exposed lands to brief, intensive periods of grazing, manuring, and trampling, (3) intensive "hoof action" is necessary to break up soil and incorporate organic matter, (4) rangelands degrade in the absence of intensive grazing, and (5) therefore, by very frequently rotating cattle, (ostensibly) the modern equivalent of ancient wild herds, through small paddocks of land which are then subject to intense but brief grazing, we can improve rangeland health, produce vastly more meat on the same land, and sequester *all* anthropogenic carbon emissions.

While benefit to IRG has a somewhat plausible theoretical basis, it has been criticized in the scientific literature, with very few studies finding any favor to this strategy [420, 419]. Indeed, from my own review of the subject I conclude that there is little evidence to support the idea that a rotational grazing strategy is of any benefit over continuous grazing, increasing stocking densities by the amounts proposed would almost certainly harm all existing rangelands, and it is pure fantasy to suppose that it could sequester any more than a tiny fraction of humanity's carbon emissions,as elaborated below.

IRG was popularized in the 1960s in sub-saharan Africa, and the idea has been aggressively promoted by Allan Savory since then. Surprisingly, governmental agencies in North America and Africa have encouraged the idea, despite dubious evidence of benefit. As reviewed below, above-average rainfall, which dramatically increases the productivity of arid and semi-arid rangelands, coincided with early phases of adoption in both regions, but in either case the parting of the rains put the lie to the notion that IRG had anything to do with increased yields [422], and multiple reviews of dozens of studies [423, 425, 426] show absolutely no experimental evidence of benefit to IRG over simpler continuous grazing (despite theoretical arguments advanced by some authors), and even suggest that continuous grazing is the more productive strategy [426]. Moreover, many rangelands in the US, especially west of the Rockies, did *not* evolve under heavy herd grazing pressures, undermining the evolutionary logic supporting IRG [419], and the claim that all grasslands degrade in the absence of grazing is patently false, with the opposite more often observed [419, 420].

Finally, the idea that mostly arid and semi-arid rangelands, which are characterized by intrinsically low productively, could ever absorb even a fraction of humanities carbon emissions is nonsense, *regardless* of grazing strategy [409, 413, 419] and there is little evidence that IRG results in greater soil organic carbon stores than a continuous grazing strategy [413]: while one study by Teague et al. [418] observed slightly higher SOC concentrations under IRG than continuous grazing, Allen et al. [415] conversely found SOC to be lower under IRG across 18 Australian properties, and most studies have found no significant differences between grazing strategies [416, 414, 417, 411, 412, 410]. Since range productivity appears to be similar between IRG and continuous grazing [425, 410] there is also little theoretical reason to think that IRG would improve carbon stores. I now further discuss the historical literature comparing rotational and continuous grazing strategies, where the focus has primarily been on productivity, not carbon stores.

21.3.1 Comparisons of grazing strategies

There are two basic grazing *strategies*: (1) continuous grazing (CG), and (2) rotational grazing (RG). Continuous grazing is the traditional method, and it is just what it sounds like: cattle are allowed season-long access to a single paddock. Rotational grazing was first described over two hundred years ago, and rotational systems were widely implemented beginning in the 1950s, in hopes that they could represent a solution to the severe overgrazing of the previous century [425]. There are many versions of rotational grazing, but all involve dividing a range into multiple paddocks, and then rotating the herd through these paddocks. This increases the intensity of grazing in the active paddock, but then provides a rest period for the vegetation to recover. The more paddocks, the higher the grazing intensity.

Multiple reviews since the 1960s have concluded that there is little difference between the two systems in terms of either range condition or livestock productivity when the stocking rates, i.e. the number of animals per hectare, are similar [425]. Indeed, the literature overwhelming indicates that stocking rate is the key management variable [422, 425]: In general, the more livestock on a piece of land (within the range of commercial stocking densities), the more it is degraded. Increasing the stocking rate also increases animal productivity (as measured in kg beef/hectare) up to a point, beyond which the resource base is overwhelmed and productivity begins to decline. Overstocking can yield short-term gains, but is not sustainable longer-term, and it is well-understood that overgrazing has been the major driver of pasture and rangeland degradation over the last century. How many cattle is what matters; it matters little how they are grazed, and much of the literature comparing CG and RG is confounded by different stocking rates between plots.

This conclusion is also supported by a critical review by Joseph and colleagues [421] of the so-called "Charter Grazing Trials" conducted in Zimbabwe between 1969 and 1975, the major research foundation for Savory's IRG system. Overall, these trials included two test (IRG) and two control plots, each about 2,000 acres in size. The tests happened to occur during a period of above average rainfall (24% higher than long-term average), and IRG plots were stocked at about 50% higher density than the controls. The IRG plots did indeed yield 30–40% higher beef production (from 50% more cows), but at the cost of poorer forage, lower individual cow weight, and an increase in supplemental feeding from outside (an extra nutritional input, confounding the test further). Moreover, the control plots were periodically burned (IRG plots were not) to eliminate excess shrub and vegetation growth, strongly suggesting that they were comparatively under-stocked. There was no significant difference in grass or vegetation cover type between the plots. Joseph et al. concluded [421], quite validly in my opinion, that the increased stocking density in the test plots explained the higher beef yield, not the grazing strategy, and that the above average rainfall during that period was the factor that allowed higher stocking densities in the first place (as reviewed, other ranches that increased stocking and productivity at this time using IRG were later forced to drastically decrease or even eliminate grazing in the face of severe land damage when rainfall returned to historical norms).

This was not a new critique, and in a very worthwhile 1987 paper, Jon Skovlin [424] expressed astonishment at the acceptance of Savory's IRG system in North America, following years of apparent failure in sub-Saharan Africa. Even at this time Skovlin noted that increased stocking in Savory's experiments was likely enabled by very high rainfall, with dramatic cutbacks in stocking necessary once drought set in. Skovlin also documented decreased weight gain and increased stress in cattle subjected to IRG, and cited a 1982 World Bank study that found no justification for claims of long-term doubling or tripling of stocking rates under IRG, and furthermore, that most rancher clients who had adopted Savory's IRG method had since reverted to traditional, lower-stocking grazing.

Holechek and colleagues reviewed a number of classical long-term studies on grazing systems, including rotational systems, in [422], as well as 13 studies of short-term IRG grazing systems at 13 US locations [423]. Contra Savory's claim that the hoof action, i.e. trampling, of a large number of animals will improve soil health and increase water infiltration, it was very consistently found across studies that trampling compacted the soil, reduced water infiltration, greatly increased erosion, decreased soil fungus, decreased soil organic carbon, and furthermore did not affect incorporation of organic litter into the soil. Compaction and erosion both increased with stocking density, again contradicting one of Savory's central claims. As with other reviews and individual studies, there was little difference in vegetation or forage production, and beef production was similar for similar stocking rates regardless of grazing strategy (except for one study which found lower cattle weights under IRG).

The most significant recent publication was a 2008 synthesis paper of 41 experiments comparing CG and RG [425]. Across all studies, in terms of animal production per unit of land, 50% showed no difference between the strategies, 34% favored CG, and 16% favored RG. Plant productivity was comparable in 83% of studies, while 13% favored RG and 4% CG. From this, it would seem to be a wash. However, this "vote-counting" methodology is overly simplistic, and recently a more sophisticated meta-analysis of the same data-set was performed [426], which found that *continuous* grazing yielded 7% higher animal production in terms of kg/head ($p < .0001$), and 5% higher animal production in terms of kg/hectare ($p < .0001$); both differences were highly statistically significant. There was possibly a very slight advantage to RG in terms of plant productivity (2%), but this may have been an artifact of lower overall foraging in the RG group, and was not considered reliable by the authors.

It is notable that there was no difference between the two strategies in studies with larger land areas ($>$ 1,000 hectares) [426], which may be more representative of large commercial ranches, and the analysis suggested a *possible* benefit to RG with longer rotational periods, in more arid environments, and with more seasonal weather variability. In any case, the difference between the strategies was small, and the preponderance of the evidence actually seems to favor continuous grazing.

Several other authors, most notably the group of Teague and colleagues (see e.g. [418]), have promoted rotational grazing in the literature almost entirely on theoretical grounds, and have strongly criticized and dismissed the empirical literature. Nevertheless, at some point theory must yield to facts, and over 60 years of study have failed to show any meaningful benefit to rotational grazing systems, intensive or not, and dozens of trials have failed to support Savory's method, including studies overseen by Savory himself.

21.3.2 Final word

I have spent the time discussing this controversy largely as a warning against "magic bullet" thinking: it is possible that intensive rotational grazing may have very modest benefits in some circumstances, but it is a dangerous delusion to believe it can single-handedly reverse global warming and feed the world. Much like half-baked geoengineering schemes, it represents an appeal to the hope that there really is a *deux es machina* that can save us, that the problem of global warming is not one fundamental to the Western lifestyle. The claim itself makes no sense with respect to basic ecological constraints: rangelands can only produce so much vegetation, and they can only store a limited amount of carbon. Cattle produce methane regardless, and overstocking degrades the land no matter what. Consuming cows for food as anything other than a relatively rare luxury item is too environmentally destructive to be sustained. This includes grass-fed cattle, it clearly includes grain-finished cattle, and it includes "holistically managed" cattle.

21.4 Dairy

21.4.1 Overview of production system

Dairy systems are the most complex of modern livestock systems to analyze, chiefly because they yield both milk and meat, with meat coming from the calves born yearly to each milking cow and from spent cows culled from the heard. The dairy production system is somewhat similar to the cow/calf beef production system, but with important differences. Typically, dairy cows are impregnated yearly, and after a gestation time of nine months (similar to humans), they give birth to a calf and begin lactating. Recall that mammals *do not* lactate unless they have recently given birth, and yearly impregnation with subsequent calving is necessary to maintain milk production. Several straightforward handbooks for dairy operation are available through the FAO, e.g. [428] and [427], which I have partially relied upon for the following discussion.

The calf is typically removed from the mother no later than two or three days after birth (and sometimes within hours). Similar to humans, mammals that we are, the first milk produced is known as *colostrum*, a thick, antibody-rich substance that is essential to imparting passive immunity against infection for the first few months of the calf's (or baby's) life [427]. Thus, calves are allowed to stay with their mother at the beginning chiefly that they may suckle of the all-important colostrum, which is not marketable for human consumption anyway. These calves are then raised individually in hutches until weaning, and ultimately enter the beef system or are retained as replacement milk cows.

With the taking of the calf, we now have a new mother cow producing milk, and one that has been bred to produce far in excess of what a calf needs, and she, along with the rest of the milking herd, is milked two or three times daily. When not being milked, the cows may feed at pasture or indoors. About three months after calving, the lactating cows are again impregnated. Milk production peaks about 6–8 weeks after calving, and then slowly decreases until ceasing about two months before the next calving [427]; this two month interval is known as the dry period, and the lactation, calving, and milk production cycle is illustrated in Figure 21.4.

As with the cow/calf beef systems, some fraction of the cowherd is regularly culled. In the US, cows first calve at about 2 years of age [322, 432], and then last, on average, about 2.5–3 more years (i.e. three total lactations, with one cut short) before culling[1]. Thus, out of 100 milking cows, as many as 30–40 may be culled for meat yearly, and 30–40 female calves will be retained as replacement heifers. The remaining female and male calves will be sold into the beef production system. While a few unfortunates become veal, the veal market has collapsed in recent decades (as a consequence, one should note, of collapsing consumer demand), and most dairy calves will enter the beef system, generally going first to a stocker system and then ultimately to feedlot for finishing and slaughter. A very small number of bulls are also maintained for breeding purposes (or artificial insemination may be used). The dairy system and its connection to the beef system are illustrated in Figure 21.5.

[1] The FAO gives a per-annum 34% adult cow replacement rate for North America, suggesting 3 years before culling. A shorter milking lifetime of 2.5 years is calculated using the total US dairy herd size of 17,515,149, with 9,762,171 either milk cows or heifers that calved (2012 Agricultural Census, Table 17), and assuming that all other cattle are replacement heifers that take two years to first calving.

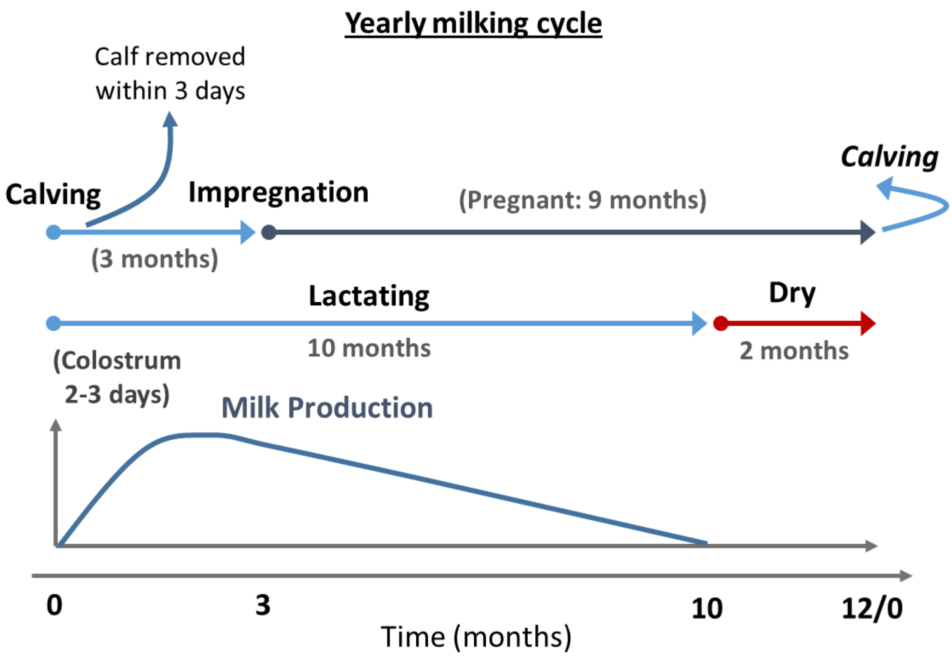

Figure 21.4: Ideal yearly milking cycle for a dairy cow. A cow gives birth at month 0, and after producing antibody rich colostrum, essential to the newborn calf, for two or three days, she lactates for about 10 months, with peak milk supply occurring at 6–8 weeks, as shown at the bottom graph. She is impregnated at the third month to yield another calf at the end of the year, following a two month "dry" period, thus restarting lactation for another yearly cycle.

21.4.2 Survey of lifecycle analyses and milk/dairy emissions factors

- On a per-kg basis, production of fat and protein corrected milk (FPCM, 4% fat and 3.3% protein) in the US likely generates 1.5–2.0 $kgCO_2e/kg$, with 1.75 $kgCO_2e/kg$ a reasonable best estimate.
- Using energy or protein as the basis of conversion, common solid cheeses have mass-based emissions factors around 10–15 $kgCO_2e/kg$, or about one-fourth to one-fifth the EF of retail beef cuts, but two or three times higher than the (mass-based) EFs for poultry and pork.

Emissions sources from milk production are, quite naturally, very similar to those for beef production, and mainly entail CH_4 from enteric fermentation (the largest single source, at 52% in an FAO analysis [432]), N_2O from manure, upstream emissions from feed production, and a small amount of CO_2 from on-farm fuel and electricity use. In the US, these on-farm factors account for about 75–85% of all lifecycle emissions [432, 431]. The remainder, beyond the farm gate, are attributable to further milk processing, refrigeration, and transport.

A large number of lifecycle analyses have examined the dairy system, generally arriving at an emissions factor on the order of 0.75–2.0 $kgCO_2e/kg$ milk (with most around 1.5 $kgCO_2e/kg$) for European (the majority of studies) and American systems (see [430, 431] and references therein), where the functional unit is fat and protein corrected milk (FPCM), assumed to be 4% fat and 3.3% protein, also known as energy-corrected milk (ECM) [430, 432][2] That is,

[2]The energy contained in any particular milk can be estimated from percentage fat and percentage protein, according to empirically derived regression equations. The IFCN formula for normalizing to 4% fat, 3.3% protein

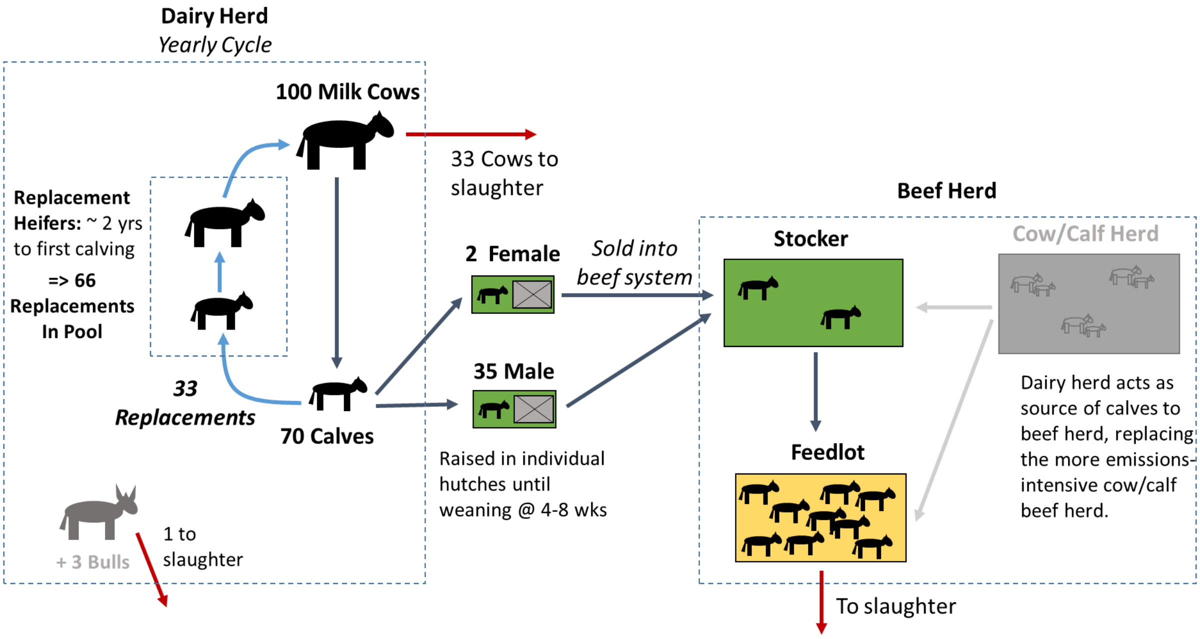

Figure 21.5: Schematic for the (ideally) yearly dairy herd cycle. From 100 milk cows, perhaps 70 surviving calves are born. Since milk cows last less than three years before culling, this translates into 33 cows sent to slaughter, and 33 female calves retained as replacements. Since it takes at least two years before first calving and "graduation" to milk cow status, the replacement pool is 66+ heifers strong. All calves are raised until weaning in individual hutches, and those not retained enter the beef system, typically to a stocker system, and then to feedlot and slaughter. Therefore, the beef cow/calf herd is cut out when dairy calves enter beef production. Note that the most beef cattle in the US come from a cow/calf, beef-only production system.

emissions are normalized based on the *energy* content of the milk produced, a necessity for any coherent analysis, given the wide array of both liquid milk products (e.g. 2%, 1%, skin milk), and other dairy, chiefly cheese, that raw milk is processed into. Further, since the dairy system produces both milk products and meat, any analysis must allocate emissions between these two products. This is commonly done on the basis of either protein or energy content of these two products, with 75–90% of emissions attributed to milk [430, 432].

An extensive analysis by the FAO [432], produced as a follow-up to *Livestock's Long Shadow*, examined the global dairy system, and found it to be responsible for 4.0% of global anthropogenic GHG emissions. Per unit emissions ranged from 1.3–7.4 kgCO_2e/kg FPCM at the farm gate, with developing countries having much higher emissions than Europe and North America. Further processing emissions where about 0.225 kgCO_2e/kg FPCM for the USA (with emissions to process different dairy products similar except for fermented milk/yogurt, which are about twice those of fluid milk or cheese), suggesting about 1.525 kgCO_2e/kg FPCM at the retail level.

A slightly more recent series of US-specific analyses, performed by multiple authors but summarized by Thoma et al. [431], similarly suggested about 1.63 kgCO_2e/kg of milk at the retail level (including 12% waste upstream of retail), and, including both consumer-level energy use for refrigeration, etc. and 20% consumer waste, 2.05 kgCO_2e/kg milk consumed. In sum, disregarding consumer-level waste, one may reasonably assume that emissions are on the order of 1.5–2.0 kgCO_2e/kg FPCM purchased at retail, with 1.75 kgCO_2e/kg FPCM a reasonable point-estimate (I use this slightly higher number than the point estimates of either [432] or [431] to correct for an updated methane GWP).

Given that both milk and beef are products of our friend the cow, it is salient to compare the emissions intensities of these two foods. While beef is over 20-times as emissions-intensive on a mass-basis (approximately 40–50 kgCO_2e vs 1.75–2.0 kgCO_2e per kg), this is not the appropriate comparison, since a much higher fraction of milk is water. On either an energy basis (i.e. CO_2e per kcal) or protein basis (kgCO_2e per kg protein), beef is about four to five times as emissions-intensive (using FAO numbers for beef carcass, we have 3,230 kcal and 165 g protein per kg beef); Figure 21.6 graphically summarizes these comparisons.

Emissions factors for non-milk dairy

Given an emissions factor for FPCM, and estimates for additional processing energy for other dairy products (per the FAO), we can derive approximate emissions factors for commonly consumed items such as cheese and yogurt on a mass-basis (as mass is most readily discovered at the retail level), converting from FPCM either on the basis of energy or protein content. Figure 21.7 gives such emissions factors for several common cheeses and yogurt, assuming 1.75 kgCO_2e/kg FPCM. Note that the EF is slightly higher on a protein basis, and 10–15 kgCO_2e/kg is a reasonable rule (or range) of thumb for common solid cheeses, i.e. about one-third the impact of beef on a mass-basis.

is given by the FAO [432]. I use the regression given by [430]; one may also consult [429]. Standard energy content of FPCM is about 748 kcal/kg [429], but this appears to be combustion energy. Based on published milk nutrition information, I calculate that digestible energy is about 89% of combustion energy, or about 665 kcal/kg of FPCM.

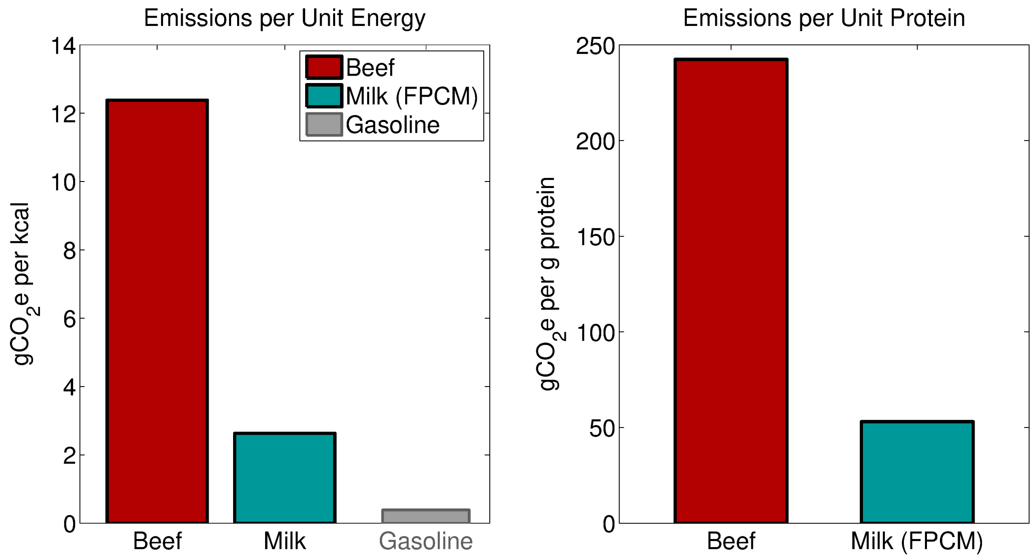

Figure 21.6: Approximate carbon emissions of milk (and most milk products) versus beef, on caloric and protein bases. The energetic comparison is given on the left; as a curiosity, the emissions per kcal of energy in gasoline is included for comparison, showing that these food products actually embody much higher emissions than fossil fuels (although the comparison is not exactly fair, as men cannot eat oil). The protein-based comparison is shown on the right, and as can be seen, the relative impact is similar on either basis.

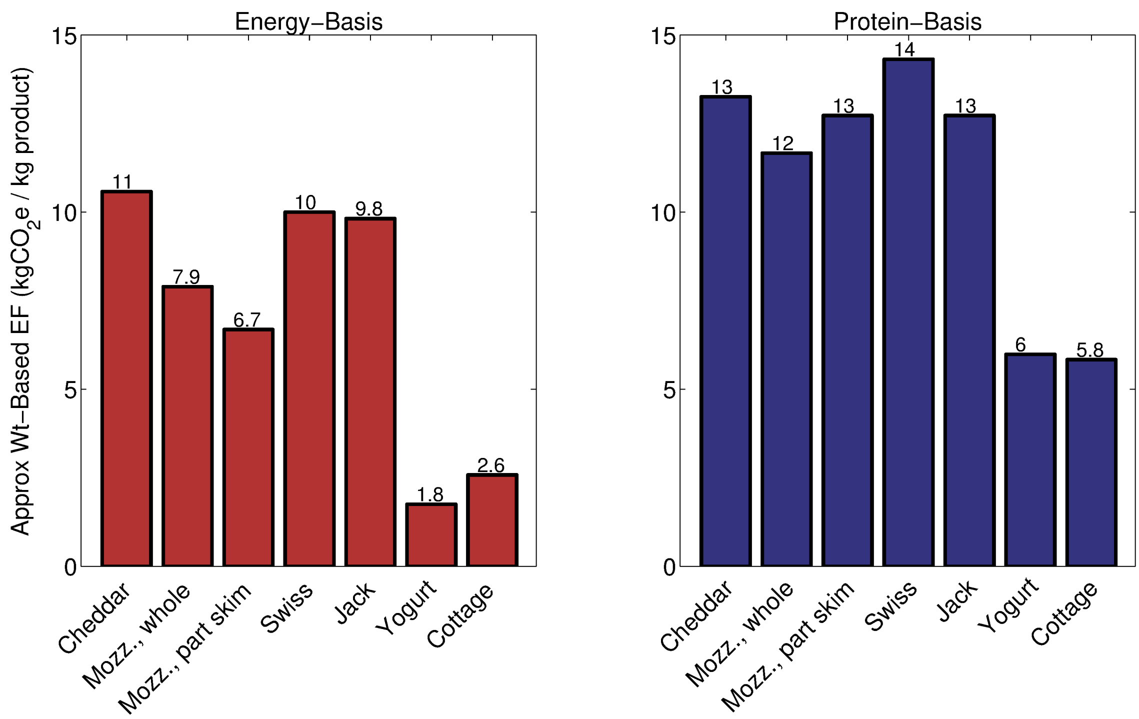

Figure 21.7: Approximate carbon emissions factor for common cheeses and yogurt, on the basis of weight, converting from an EF of 1.75 $kgCO_2e/kg$ FPCM either on the basis of food energy (left panel) or protein (right panel).

21.4.3 Dairy-Beef system connection and emissions corrections for beef

- Meat ultimately sourced from dairy herds has a 33–50% lower carbon footprint than beef-only herds, and perhaps 20% of US beef is so sourced. Correcting for this, the likely carbon footprint of retail beef decreases slightly, from about 35–50 kgCO_2e/kg to 32–46 kgCO_2e/kg.

The carbon footprint of beef produced as a side-product of the dairy system has a somewhat lower carbon footprint than beef produced in designated beef-only production systems, e.g. the cow/calf-stocker-feedlot process discussed in Section 21.2. This is for two reasons: (1) milk cows culled have spent much of their life producing milk, and thus not all emissions from feed, etc. are attributable to biomass accumulation, and (2) calves that exit dairy farms to enter beef production essentially skip the cow/calf stage of beef production, the most emissions-intensive phase in beef-only herds.

Using data from Pelletier et al. [439], I calculate that, if a calf was raised entirely in a stocker to feedlot system (i.e. excluding the calf-cow phase), emissions per kg boneless beef would fall from about 40.5 kgCO_2e/kg beef to perhaps 27 kgCO_2e/kg beef, a 33% decrease. A more detailed analysis of Irish beef production [433] suggested emissions savings of 33–36% using calves from a dairy system rather than a designated beef system, very similar to my rougher estimate.

The FAO analysis [432] gave, as a global average, emissions intensities of 15.6 kgCO_2e/kg carcass weight and 20.2 kgCO_2e/kg carcass weight for culled dairy cows and fatted calves, respectively. If we assume that culls from the US system are similarly about 25% lower than fatted dairy calves, then we can reasonably estimate that meat from dairy culls has only half the associated emissions of meat from beef-only system.

So, the question now is: how do these lower emissions factors for dairy-sourced meat affect our estimate of the carbon footprint of the average supermarket beef purchase? There is no data that I am aware of tracking exactly how many cattle slaughtered for meat come from either dairy culls or dairy calves sold into meat production, but one can reverse-engineer a reasonable guess. Per the FAO, in the US about 34 million cattle were slaughtered for beef in 2012, while the 2012 USDA Agricultural Census gives 9.25 million milk cows. Assuming 77% fertility and an 8% calf death rate [432], we have about 6.5 million surviving calves. If 34% of milk cows are culled yearly, that means 3.15 million cows sent to slaughter, 3.15 million calves kept as replacements, and 3.35 million calves entering the beef system, with an equal number of (former) calves therefore slaughtered from past years. Thus, in total, around 10% of beef may come from culls (given that adult cows are slightly heavier than beef steers and heifers at slaughter [432]) and 10% from former dairy calves. Supposing, as above, that fatted dairy calves are 33% lower in their impact, and culls 50% lower, then the average retail beef emissions factor would decrease by 8.33%, from around 30–50 kgCO_2e/kg beef to 28–46 kgCO_2e/kg beef.

21.5 Monogastrics: pig, chicken, and egg

Monogastric ("single stomach") animals, such as the pig, chicken, and horse, are much more efficient at converting feed to biomass than ruminants, and methane from enteric fermentation in monogastrics is negligible. Thus, the (per-unit) carbon emissions attributable to monograstric production are nearly an order of magnitude lower than those due to beef production, and are comparable to or slightly lower than diary emissions. While Americans consume almost three times as much pork, chicken, and eggs (on a weight-basis) as beef, the former systems all together probably only generate 30–50% the greenhouse gases, and require a fraction of the land as the beef system. Monogastric production is roughly comparable in scale to dairy, with the monogastric system as a whole generating about 78% of the calories as the dairy system (using FAO numbers for fresh carcass nutritional content), while likely yielding on the order of 60–80% of the greenhouse gases. However, the monogastric system yields slightly more protein than dairy (perhaps 13% more), and so is somewhat less emissions-intensive on this basis. Land requirements (mainly in the form of pasture) are also at least two-fold higher for dairy [457].

Now, although monogastric systems are relatively efficient at converting feed to edible products, their per-unit impact is still perhaps two to tenfold greater than comparable plant sources of protein, and due their sheer scale, these production systems still represent a non-trivial environmental impact, and modern animal confinement systems entail very serious animal welfare issues as well.

As with beef, monogastric production systems generally entail a stock of breeding animals, which produce a string of offspring that are then "finished" for slaughter (or raised as laying hens), with a portion retained in the breeding population as replacement for culls. Carbon emissions (as well as land-use, etc.) must be calculated across the entire system to obtain accurate per-unit emissions factors.

Egg and chicken meat ("broiler") production systems are typically separate in the US. In broiler systems, day-old chicks from the breeding flock are raised in confined housing (but not in individual cages, and the "cage-free" label when applied to chicken *meat* is utterly meaningless marketing), fed a soy and maize-based diet, and generally brought to slaughter within six weeks. In egg systems, day-old chicks become "pullets," i.e. young birds not yet ready to lay, who then graduate to the laying hen flock, the majority of whom (in the US) are housed in battery cages and then culled after a few years of laying (the meat from such spent hens does not generally reach the retail market).

Exact emissions factors are uncertain, but overall my reading of the literature suggests a likely range of about 5–7 kgCO_2e/kg pork, 3–6 kgCO_2e/kg poultry, and 2–4 kgCO_2e/kg egg, at the production level. Similarly, Heller and Keoleian [321] averaged results from several studies, giving 6.87 kgCO_2e/kg meat for pork, 5.05 kgCO_2e/kg meat for poultry, and 3.54 kgCO_2e/kg for eggs. However, these products vary in their energy and protein content, and beef and pork carcass meat (pork especially) is relatively high in calories and lower in protein, compared to poultry meat, which complicates slightly any weight-based comparison of lean retail cuts. On a caloric basis, eggs and pork may have the lower per-unit emissions, while on a per-protein basis pork is worst; eggs and chicken meat are similar, likely with a slight advantage to chicken.

Alternative production systems focusing on improved animal welfare, e.g. free range chicken and eggs and deep-bedded swine systems, tend to require slightly more feed but less on-farm energy, and may typically generate around 10–15% more greenhouse gas emissions (and require $<$10% more land) than conventional confinement systems. However, these relative differences usually amount to a trivial $<$0.5 kgCO_2e/kg meat or egg in absolute terms, a minor and highly defensible trade-off for improved animal welfare, at least in my view. The following sections review some of the literature supporting my emissions factor estimates.

21.5.1 Poultry

Before the Second World War per capita US egg consumption was similar to the present day, but chicken meat was a very minor component of American diets, with annual consumption less than five kg, about one-tenth of red meat consumption. The post-war years, however, saw Americans learn to love the chicken, as cheap chicken accompanied a revolution in poultry production. Compared to ruminant meat, chicken is low in carbon emissions for two major reasons: (1) chicken has a very high feed conversion ratio (FCR) and nitrogen retention fraction, i.e. a larger proportion of feed is converted to bird mass and protein (note that reduced feed requirements reduce both upstream feed production emissions and downstream manure emissions), and (2) birds, as monograstrics, emit essentially no methane from enteric fermentation.

As with pork, carbon emissions from chicken production come chiefly from feed production, manure management, and farm operations. A 2013 FAO [387] analysis estimated North American broilers to generate about 4.5 $kgCO_2e/kg$ carcass weight, or 7.5 $kgCO_2e/kg$ boneless meat (assuming boneless retail weight is 60% of carcass weight, per USDA data), but this estimate is high compared to other US- and UK-specific estimates. Several slightly older analyses, as reviewed by Nijdam et al. [390], gave estimates in the 2–6 $kgCO_2e/kg$ meat range, and averaged just about 3 $kgCO_2e/kg$. Pelletier [434] similarly estimated US broilers to cost 1.395 $kgCO_2e/kg$ live weight, or about 2.8 $kgCO_2e/kg$ boneless meat. A study of the UK broiler systems [435] gave 4.41, 5.13, and 5.66 $kgCO_2e/kg$ meat for standard, free range, and organic systems, respectively. Analyses have consistently concluded that a majority of emissions are attributable to feed production (almost entirely maize- and soy-based feed in the US), with on-farm energy generally coming in second, and manure management usually a very small contributor.

Several other studies suggest the greenhouse gas impact of both free range broiler [435] and egg [437, 442, 436] production to be only 10–20% higher than for conventional confinement systems, mainly due to modestly increased feed requirements. Almost all land associated with poultry/eggs is upstream, at the level of feed production, and the increased on-farm land requirement for free-range flocks is likely well under 10% [437]. Even a 20% increase in carbon footprint, from a baseline of 3–6 $kgCO_2e/kg$, corrects to just 3.6–7.2 $kgCO_2e/kg$, with a midpoint estimate of 5 $kgCO_2e/kg$ meat increasing to only 6 $kgCO_2e/kg$ meat. Thus, the improved animal welfare in free-range systems is, in my view, worth the small (absolute) land and carbon cost, and can (and should) be offset at the individual level by modestly decreased overall meat consumption. Finally, "organic" is not synonymous with "free range," and organic broiler systems may carry a somewhat higher cost than either conventional or free range systems [435].

21.5.2 Pork

On balance, the literature suggests somewhat higher emissions for pork than poultry, with feed production similarly dominating as the number one source of emissions, but with manure emissions also fairly significant, and more important than for poultry. The FAO analysis [387] gives about 4.75 $kgCO_2e/kg$ carcass weight for North American pig systems, translating into 6.6 $kgCO_2e/kg$ boneless meat (boneless weight is about 72% of carcass weight per the USDA). Pelletier and colleagues [439] estimated swine production emissions in the Upper Midwest to be about 4.9–6.1 $kgCO_2e/kg$ meat for conventional industrial systems (assuming 50% of live weight is converted to boneless meat), and 5.0–6.7 $kgCO_2e/kg$ for small-scale, deep-bedded "niche" systems. In a report commissioned by the National Pork Board, Thoma et al. [438] gave 5.9 $kgCO_2e/kg$ boneless meat as an average across US swine. Finally, eight studies reviewed by Nijdam et al. [390] gave a range of 4–11 $kgCO_2e/kg$ meat for pork (with 5 $kgCO_2e/kg$ typical), and Heller and Keoleian [321] gave 6.87 $kgCO_2e/kg$ as their study average.

21.5.3 Eggs

A recent and quite thorough analysis by Pelletier et al. [440], gave 2.1 $kgCO_2e/kg$ egg for US production systems in 2010. Assuming an average egg weight of about 60 g, this translates into 0.1260 $kgCO_2e/egg$, or just about 1.5 $kgCO_2e$ for a dozen eggs. This study followed a more theoretical one by the same authors [441], which suggested emissions in the 2–5 $kgCO_2e/kg$ egg range. Emissions sources are dominated by feed production, with manure management the only other major contributor. This is fairly consistent with the FAO analysis [387], which gave about 2.8 $kgCO_2e/kg$ egg for North American flocks. Other emissions estimates, as reviewed in [440] and [390], have also generally ranged from <2 to about 5 $kgCO_2e/kg$ egg, and the balance of the literature seems to suggest an emissions factor closer to 2 $kgCO_2e/kg$ egg as more likely.

Of note, the FAO analysis found emissions from backyard chicken flocks to be comparable to those from industrial systems, mainly because, while backyard flocks were less efficient at converting feed to growth and had increased manure emissions, they could subsist on more marginal feedstock and their feed did not have the associated land use changes of some industrial systems. Leinonen and colleagues [436] calculated UK emissions factors of 2.92, 3.45, 3.38, and 3.42 $kgCO_2e/kg$ egg for caged, barn (i.e. cage-free), free range, and organic egg production, suggesting only a slight carbon cost to improved welfare. Along the same lines, Dekker et al. [442] gave 2.24 $kgCO_2e/kg$ egg using battery cages and 2.74 $kgCO_2e/kg$ under free range conditions (organic and barn systems were intermediate), for Dutch egg systems. Meta-analysis of this and several other comparisons found no significant difference between the GWP for conventional and organic eggs, although lower feed conversion efficiency in organic systems does increase the land footprint [442, 467].

21.6 Seafood

- The carbon impact of fish ranges from <1 $kgCO_2e/kg$ meat to over 30 $kgCO_2e/kg$ meat, with mussels and herring examples of low-impact fish, while deep-trawled shrimp and various rockfish are high-impact. Salmon and tuna are middling in their impact (3–10 $kgCO_2e/kg$) and similar to chicken or pork.
- The carbon impact of wild-caught seafood is dominated by diesel fuel used to operate fishing gear, with deep trawling most energy-intensive, in addition to the terrible damage it does to the seafloor.
- Shrimp is the top seafood in the US, and the carbon impact may range from about 7–38 $kgCO_2e/kg$ for wild-caught shrimp, while some farmed southeast Asian shrimp could have emissions of well over 1,500 $kgCO_2e/kg$, due to the destruction of mangrove forests. Shrimp should generally be avoided unless one is sure of a relatively benign source.

Americans consumed 7.0 kg (15.5 lbs) of seafood per capita, in 2015, with a somewhat uncertain impact. Seafood is often viewed as a more benign alternative to other animal products ("pescetarianism," etc.), but in fact the environmental impact of this broad category of food varies widely, with some quite sustainable, much of it deeply harmful, and most typical seafoods are probably similar, in terms of carbon emissions, to chicken and pork. The emissions factor for shrimp, the number one seafood in the US, may vary from anywhere from <10 to *thousands* of $kgCO_2e/kg$ edible meat [445, 447], depending upon the source, and so should generally be avoided. Salmon, the number two species, may have an impact in the 3–8 $kgCO_2e/kg$ range [390], while number three tuna likely generates around 3–10 $kgCO_2e/kg$ [444].

Carbon emissions vary widely with fishery, fishing method, and freight shipping mode, but overall the emissions factor may generally range from <1 to 35+ $kgCO_2e/kg$ of edible fish, but likely averages around 3–10 $kgCO_2e/kg$ fish [390]. For wild-caught fish, the carbon footprint is dominated by on-ship diesel use, and it is generally far more efficient to catch fish that dwell in the shallower levels of the open ocean ("pelagic" species), e.g. via purse seine nets, than via deep-sea methods such as bottom trawling and longline fishing; at the extreme end, bottom trawling for Norwegian lobster required just over seven gallons of diesel fuel for a single kg of meat, equivalent to a remarkable 86 $kgCO_2e/kg$ [390], about twice the carbon footprint of beef.

However, anywhere from 5 to 30 $kgCO_2e/kg$ may be more typical for deep trawling [443, 445].

Bottom trawling is also widely destructive to the seafloor and generates large amounts of by-catch. Thus, fish caught via deep trawling, which generally includes rockfish (redfish, orange roughy, Chilean sea bass, and others), some cod, halibut, and shrimp and other crustaceans, should be avoided for multiple reasons. Longline methods, while also energy-intensive, are considerably less destructive to the ocean ecology than deep trawling. Small pelagic species, such as herring, may have carbon footprints well under 1 $kgCO_2e/kg$ [445, 390].

Shrimp is worth a special mention, as it is the number one seafood product consumed in the US by a good stretch, accounting for over a quarter of all fish consumed in this country. At industrial scale, it is fished by deep trawling, and some estimates for North Atlantic shrimp come in at about 7 $kgCO_2e/kg$ meat (based on [445], and assuming 45% of live weight is edible). On the other hand, Ziegler et al. [446] calculated a much higher emissions factor of 38 $kgCO_2e/kg$ edible shrimp for industrial Senegalese pink shrimp. Furthermore, in tropical Asia, mangrove forests have been widely converted to extensively managed shrimp ponds, resulting in a massive loss of ecosystem carbon (and the ponds are abandoned after just 3–9 years due to acidification and contamination), with Kauffman et al. [447] estimating that such systems yield a staggering 1,603 $kgCO_2e/kg$ shrimp on average, about 40 times worse than beef and equivalent to almost 150 gallons of gasoline.

Finally, in addition to fishing energy, cold storage and downstream transportation also add to the carbon impact of fish, although these tend to be minor components, with the exception of transport via air freight [444] (and so any seafood known to be flown in for freshness should be shunned, and not coveted).

21.7 Emissions by mechanism

Not counting direct and indirect land-use effects, three major mechanisms account for most of the greenhouse gas impact of animal agriculture: enteric fermentation, manure management, and feed production. While these have already been extensively addressed, at least in passing, I give each a dedicated treatment here.

21.7.1 Enteric fermentation

Some fraction of the carbohydrates consumed by ruminant animals is converted into methane within the rumen of the animal. It is standard to define the CH_4 conversion factor (Y_M) as a percentage of the animal's *gross energy intake*, and standard IPCC values are 3% for feedlot cattle and 6.5% for grass-fed cattle [450], although the value may vary between 2–12% overall [451]; several studies of Canadian beef cattle have found values of 4% for feedlot and 6% for pasture cattle [451], and Todd et al. [449] measured a value of about 3.0% in US feedlot cattle. A negligible amount of methane is produced by milk-fed calves.

The Y_M factor tells us the energy content (not mass) of methane produced for a given amount of food energy fed; since the energy content of methane is 55.65 MJ/kg (15.46 kWh/kg, HHV) [450], we can then convert to $kgCH_4$ and the CO_2 equivalent. For example, suppose daily energy intake for one feedlot cow is 30,000 kcal, equal to 125 MJ. If 4% of this energy turns into methane, we arrive at 90 gCH_4 per day, which on a yearly basis amounts to 32.85 $kgCH_4/yr$, and 1.12 metric tons CO_2e on a 100-yr GWP basis.

Several factors affect the CH_4 conversion factor, with the major factor the digestibility of the feed. Grasses and other forage (and low-quality agricultural byproducts) are less efficiently digested, and digestion depends more heavily on the rumen for forage than grains [448]. Indeed, the major evolutionary advantage of a rumen is that it allows some energy to be extracted from cellulosic carbohydrates that are otherwise indigestible, but this process is less efficient than absorbing simpler carbohydrates from grain. It is generally found that the more ruminally digestible carbohydrate consumed, the higher the methane emissions [448].

It therefore follows, and has been consistently observed, that cattle fed a high-forage diet (e.g. grass-fed) convert about 50–115% more of their feed to methane than those fed diets very high ($> 90\%$) in grain, especially corn-based diets [448, 451, 449]. A second factor observed to affect methane production is feeding rate [448]. Heavy feeding seems to reduce the CH_4 conversion factor (perhaps because food passes more quickly through the digestive tract, spending less time in the rumen). Additionally, this leads to more rapid weight gain, shorter time to slaughter, and thus decreased CH_4 emissions per kg of meat due to the combined effects of less time spent alive and emitting, and a lower per unit feed CH_4 emission rate during life. The depressing conclusion is that purely grass-fed beef is no solution at all to the environmental harms of cattle ranching, and the more difficult task of meaningful dietary shift, rather than simply a shift in labelling, is needed to overcome them.

21.7.2 Manure management

Manure, a mixture of both urine and dung, is a valuable source of all three major crop nutrients, nitrogen, phosphorus, and potassium, although it is particularly valued as a nitrogen source, and it is a major external source of fertilizer in organic farming systems (the extent to which this represents unsustainable mining of other soils and/or a masking of conventional synthetic nitrogen input via processing through an animal's digestive tract is discussed in Section 22.1.4). However, manure management is also one of the primary agricultural sources of greenhouse gases, mainly nitrous oxide formed through nitrification/de-nitrification of manure nitrogen and methane resulting from anaerobic manure storage systems. For the first part of this discussion, I focus on nitrogen and nitrous oxide, and defer a brief discussion of methane emissions to Section 21.7.3.

Manure may be deposited either on pasture by grazing animals or within housing. For theoretical analysis, overall manure N may be straightforwardly calculated as the balance between feed N input and N retained either in animal growth or products, e.g. milk and eggs. To a first-approximation, some fraction of this excreted N, which we may label F_{N2O}, then ultimately evolves via the nitrification/de-nitrification pathway to N_2O, with the exact fraction varying with climate, animal species and diet, manure storage system, etc. Our basic equations quantifying N_2O emissions from an animal manure system are therefore

$$N_{\text{Manure}} = N_{\text{Feed}} - N_{\text{Retained}} = N_{\text{Feed}}(1 - F_{\text{Retained}}), \tag{21.1}$$

$$N_2O_{\text{Manure}} = \frac{44}{28} F_{N2O} N_{\text{Manure}}, \tag{21.2}$$

where N_x denotes mass of some nitrogen pool and F_x denotes a fraction, e.g. F_{Retained} is the nitrogen fraction retained in animal products. From the first of the above equations, two obvious methods for reducing warming potential from animal manure are (1) reduce nitrogen in feed, and (2) increase the fraction of nitrogen retained. The first is achieved by balancing protein requirements with intake, i.e. avoiding excessive protein in the diet [452]. As reviewed by Rotz [452], various lower protein feeding strategies reduced N excretion by roughly 10–35% in swine and poultry, while in cattle low protein diets may reduce N excretion by up to 70%, relative to high protein diets.

Now, the fraction of nitrogen retained varies markedly by animal system, with ruminant meat production by far the lowest: N retention is 10% or less for beef production [452], and the IPCC default value is 7% [450]. Dairy is more efficient, typically about 20–30% [452, 450, 453], while poultry and swine raised for meat retain 30–40% of feed nitrogen [452, 450]. Near the theoretical limit, 40–45% of feed nitrogen may be retained in eggs [455, 456]. It follows that manure N_2O emissions scale somewhat similarly.

A more detailed hierarchy of equations for estimating N content of feed, animal mass, and products is provided by IPCC GHG Inventory Guidelines [450], along with reasonable parameter values, but now let us turn to the fate of nitrogen once excreted and the second of our guiding equations above.

Fate of manure and manure nitrogen

It is the ultimate fate of essentially all manure to be returned to fields or pastures, although not necessarily those fields from whence it originally came. However, while the bulk matter may return, *most* nitrogen is either lost en route or within days of application to fields. Indeed, although the greater part of nitrogen contained in US crops becomes animal feed, a USDA study [459] estimated only 520,000 tonnes of manure nitrogen are applied to fields (based on Figure 2 of [459]), or less than 5% of synthetic nitrogen fertilizer initially applied (this low figure is even more impressive when one realizes that little nitrogen fertilizer is applied to soy, the major protein/nitrogen feed crop, since it is a nitrogen-fixing legume).

The most basic reason for nitrogen loss from manure is that ammonia, NH_3, is extremely prone to volatilization if not rapidly incorporated into soil, and across the various stages of manure management, i.e. housing, storage, and spreading onto fields, most nitrogen simply evaporates away [458, 452]. This is probably a good point to clarify that, in mammals, nitrogen that is absorbed into the body and not incorporated into tissues, etc. is excreted in *inorganic* (or mineral) form, mainly as urea, which, as mentioned earlier rapidly degrades into ammonia and may then volatilize. Nitrogen lost in the feces is that fraction that is not absorbed (along with some excreted nitrogen); it remains primarily in organic form, and must be mobilized to mineral form before becoming either available to plants or vulnerable to loss.

Now, we can see how a high protein/nitrogen diet not only leads to increased manure nitrogen and hence N_2O emissions as a straightforward consequence of the mass-balance described in Equation 21.2, but also increases the fraction of nitrogen excreted in urea/ammonia form (as excess nitrogen is absorbed but not utilized), and thus the fraction of manure nitrogen subsequently lost [453]. In dairy cows, for example, as one moves from a low to high protein diet, the share of nitrogen excreted in urine (vs. the feces) increases from 50% to around 67–75% [453, 454].

Returning our focus to manure management, let us briefly review the stages and losses. Overall losses are reviewed expertly by Rotz [452], while a detailed overview of nitrogen loss once manure reaches the field is given be Meisinger and Jokela [458]; the IPCC, as always, is also a very valuable resource [450]. Unless otherwise clarified, one may assume that all (or nearly all) N losses referenced are due to ammonia volatilization. At most stages, small amounts of N_2O emissions occur as well.

Housing

Housed animals obviously produce manure, and the longer the manure stays within the housing apparatus, the more time the contained ammonia has to volatilize. The amount of total manure nitrogen lost at this stage varies widely, from as little as 5% for systems where manure is removed from housing daily, to as much as 90% for cattle feedlot systems where manure is not removed for many months [452]. Note that feedlots, in addition to volatilization losses, also suffer some nitrogen loss from runoff and leaching into soil. Furthermore, some decomposition and nitrification/denitrification occurs under longer-term storage, and so, depending on the system, between 0.1–4.0% of nitrogen may evolve to N_2O [450]. Typically, one may expect nitrogen losses of about 50% across various poultry, swine, and cattle systems [452].

Storage

Once removed from animal housing, manure is usually stored long-term, up to one year. This allows manure application to coincide with the very narrow peak fertilizer demand of annual crops [452]. The most significant exception to this rule occurs in some dairy systems, where manure may be spread daily (or nearly daily) on surrounding pasture, and with little time for it, nitrogen loss can be much lower [450]. Cow/calf and pasture beef systems also see most manure deposited directly on pasture.

Since housing facilities sometimes also act as long-term storage, the line may blur a bit between these stages. In any case, manure is stored in one of three forms: (1) "solid," where partially dried manure mixed with litter/bedding is stored in stacks, and 10–40% of N is lost as the manure decomposes, with losses higher under active composting of manure (also producing N_2O); (2) "slurry," where wet manure is stored in largely static ponds or tanks, with very little N lost due to the stability of the tank; or (3) "liquid" form, common in large-scale operations, where manure is stored in lagoons that are >95% water, and recycled lagoon effluent is used to flush out manure, resulting in constant mixing and near total N loss (70 to 99%) [452].

Solid and liquid lagoon storage likely leads to some N_2O emissions from nitrification/denitrification, while nitrogen can also be lost through leachate and runoff at this stage [450].

Application

At the final step, manure is applied to agricultural fields. These fields are often part of the same farm as the animals are raised in, but increasingly there are large spatial separations between animal feeding operations and crop production. This is especially true for cattle feedlots, with 68% of such operations having no crop acreage at all, and 45% of poultry is also raised on farms lacking crops [459]. Given its bulk and high water content, it is generally impractical to transport manure long distances, resulting in a quasi-open-loop nutrient cycle, where much manure goes to crops and lands not associated with its genesis, some fields may be over-manured, and ultimately only 5% of US cropland receives manure [459]. Note that poultry litter, being drier and higher in nitrogen, is more valued and may be sold and transported further than other manures.

Volatilization, the bugbear of both the housing and storage systems, is prominent at the application point as well. Irrigating (to help work the manure into soil) or direct incorporation into soil may decrease this loss, but without some kind of immediate incorporation, essentially all remaining NH_3 nitrogen may be lost [458]. Like ammonia/ammonium introduced by grazing animals, legumes, or synthetic fertilizers, applied manure NH_3/NH_4^+ enters into the nitrification/denitrification pathway to become N_2 and warming N_2O.

Now then, since typically 25–75% of nitrogen is already lost prior to field application (during housing and storage), an additional 50% loss at the field stage implies at least two-thirds of all manure nitrogen is lost before incorporation into soil, and that therefore the remaining fraction is likely to be mainly more stable organic nitrogen, rather than volatile urea and ammonia.

Overall nitrous oxide from the manure management chain

While most nitrogen is lost from the manure management chain as ammonia, as discussed in Sections 20.1.2 and 20.1.3, detailing the nitrogen cycle, volatilized ammonia does not travel far before depositing onto soils, where it re-enters the local soil-plant nitrogen cycle, and ultimately about 1% (more or less depending on nitrogen loading and plant demand) evolves to N_2O as a direct soil emission. Furthermore, some fraction will re-volatilize, re-deposit, and partially evolve to N_2O, and thus, by iteration, we should ultimately have about 1.5% of volatilized ammonia evolving to N_2O through this cycle. This is slightly higher than the IPCC value of 1.35%. Now, of manure excreted, the fraction that becomes N_2O varies markedly with storage system, but likely averages about 2% overall. Thus, of new nitrogen that is incorporated into plant matter and subsequently passes through an animal, on the first pass perhaps 3.5% evolves to N_2O.

21.7.3 Methane from manure management

Undigested organic matter that makes up the bulk of the dry matter of manure can decompose anaerobically to produce large quantities of methane. Liquid and slurry storage systems can be largely anaerobic and thus result in very high methane emissions, while dry systems are reasonably aerobic and emit smaller amounts [450]. Manure storage systems are discussed above, and I refer the reader to the IPCC for a more detailed discussion of methane emissions [450].

21.7.4 Feed production and conversion efficiency

Feed production is a significant source of emissions for beef production, and the dominant emissions source for monogastric animal products (pork, chicken, egg). All the ways in which raising crops leads to GHGs are discussed in Chapter 20, and here I restrict discussion to a brief mention of the feed conversion factor. Peters et al. [322] derived dry matter (DM) to edible weight conversion factors of 35.5 for beef. Factors for swine, chicken, and turkey were 4.91, 4.32, and 4.25, respectively, while eggs had a DM to edible weight conversion factor of 2.62.

In terms of DM to energy and protein conversion, beef took about an order of magnitude more DM to yield the same amount of edible energy and protein, compared to all other animal products (all other animal products were quite similar in these regards). In terms of energy and protein conversion efficiency, milk was similar to the monogastric animal products. These results were qualitatively similar to those reported by Eshel and colleagues [457].