The Magnitude of Human Agriculture

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Introduction

The advent of agriculture – the science of maintaining, rearing, and expanding the cultivation of crops and animals for food security – is defining feature of humanity and is often credited with being the principal development that enables sedentary human civilization. While the harvesting of wild (i.e. not cultivated) grains has been documented as far back as 100,000 years, the specified growth and harvesting of plants and animals dates back to $\approx$ 11,000 BCE, with many of the staple animal protein sources (cattle, swine, and poultry) being domesticated within the past 10,000 years. It is not hyperbolic to state that the pursuit of food security is the primary driving force of human society.

With approximately $\approx 7 \cdot 10^9$ people on the planet today, each consuming $\approx$ 2000 kcal per day, our agricultural output must be on the order of $\sim 10^{14}$ consumable kJ per day. How have humans transformed the Earth to reliably meet this threshold? In this series of vignettes, we will explore the magnitude of human agriculture and its impact on the planet. Namely, we will consider three distinct "footprints" of agriculture.

Our first category, the physical footprint of agriculture, will consider the numbers and biomass of food sources on the planet under agricultural maintenance as well as the space on which they are grown and harvested. In doing so, we will rely on a series of data sets collected over the past $\approx$ 50 years from the Food and Agriculture Organization of the United Nations Statistical Resources (FAOSTAT) as well as myriad industry data sets capturing the nutritional requirements of livestock and annual feed production. We will conclude our summary of the physical footprint by providing a handful of key numbers that put our production of food product in a relatable scale. These numbers will drive our pursuit of the next two footprints.

[Description of chemical and aqueous footprints to go here once I make more progress on the corresponding estimations.]

The Physical Footprint of Agriculture

We will begin our exploration of the three major impacts of human impacts by considering the key observable features, namely the total amount of biomass under human agriculture management and the space in which it all happens. This section will be broken into several parts. First, we will focus on "livestock by the numbers" and see if we can make sense of the recorded numbers of animals and their agricultural products on a yearly basis. With a handle on the total number of livestock processed and/or reared per year, we will then turn our attention towards estimating the scale of crops needed to feed this livestock population in addition to the crops needed to satisfy the typical human diet. With a feeling in place for the numbers, we will turn our attention to the consideration of the spatial extent of farm land.

Livestock by the Numbers – Population

Any drive through the countryside, flight over the heartland of the central United States, or stroll through your local grocer will lead you to the same conclusion – a large amount of resources are dedicated to the rearing of animals as a protein source. In general, $\approx 30\%$ of the typical American diet is derived from animal products (Eshel et al., 2014) with the remainder coming from various crops which we will consider in depth later in this vignette.

Since 1961, the Food and Agriculture Organization (FAO) of the United Nations has kept track of myriad data reflecting the extent, efficiency, and changes in global crop and livestock production. A key statistic tracked by the FAO is the global standing population of a wide variety of livestock. Collected at approximately the same time per year per reporting country, these data, portrayed graphically in Fig. 1 (A), reflects a snapshot of how many animals livestock are under human agricultural maintenance. Chicken, both egg-laying and meat-producing varieties, are far and away the most abundant type of livestock on the planet with ≈ 20 billion individuals under human care. Second to chicken are cattle, comprising approximately one tenth that of the chicken population at ≈ 2 billion individuals. Following cattle are swine at ≈ 1 billion individuals and then all other types of livestock (including horses, other poultry fowl, sheep, goats, and others) in total representing ≈ 6 billion individuals. Taking this data together, there are on the order of ≈ 30 billion animals under the umbrella of agriculture.

It is important to note, however, that this number does not reflect the magnitude of human animal usage and rather represents the instantaneous animal burden that humans must be able to support. Poultry chicken, for example, have a remarkably short lifespan of ≈ 6 weeks from hatching to slaughter. With such a rapid generation time (courtesy of decades of artificial selection for fast-growing variants), the entire standing population could be exchanged ≈ 8 times per year. Conversely, cattle have a typical lifespan of a few years from birth to slaughter, meaning that the observed standing population is larger than that actually processed and consumed each year.

While these numbers are striking, can we make sense of them? In the coming sections, we will perform a series of estimates to see of the observed order of magnitude of population jibes with simple expectations based on a typical human dietary breakdown. We will explore our estimates in more detail using additional data from the FAO which tracks the mass of animal product produced per year as well as the number of animals processed and/or slaughtered to produce said product.

What is the typical diet? The specifics of human dietary requirements and their actual realizations is a very active field of research, and can be rather controversial. Regional diets can be remarkably diverse, making it difficult to think of the "average" diet. However, for convenience, we will make an approximation that the typical diet is something comparable to a typical Western diet, at least to within a factor of a few.

Recent work has painstakingly and carefully estimated the typical American diet that arises fro

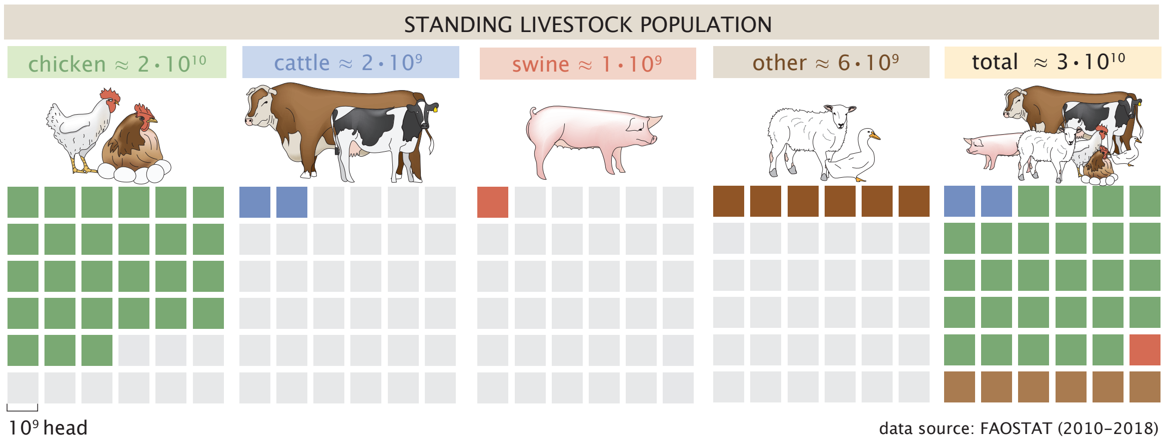

Fig. 1: **The population and biomass distribution of livestock on Earth.** The species breakdown of livestock is shown in terms of global population based on the average from years 2010 - 2018 present in the FAOSTAT livestock database. Category of "other" includes asses and mules, beehives, buffalo, camels and camelids, duck, geese and guinea fowl, goats, horses, pigeons and other small fowl, rabbits, rodents, sheep, and turkey. estimates listed in Table. A1.

Chicken We begin our estimates with the most abundant livestock species by number – chicken. As noted in our discussion earlier (see FIG XXX), our typical human will consume $\approx 1\%$ of their daily caloric intake from from chicken-derived eggs. To put this number in context, let's assume that the typical person consumes $\approx$ one-half dozen eggs per week. With ≈ 50 kcal per egg, this comes to a total of ≈ 300 kcal per week, which is $\approx 2\%$ of a weekly caloric requirement of 14,000 kcal. Given that on one-half dozen eggs per week may be a bit of an over estimate by a factor of $\approx$ a few, we can feel moderately confident that an estimate of 1% is fair for the typical caloric contribution of eggs.

With a mass of ≈ 50 grams per egg and our previous assertion of ≈ 50 kcal per egg, we arrive at a caloric density of $\approx 1\ \text{kcal} \cdot \text{g}^{-1}$ of egg consumed. Given this number we can quickly arrive at an estimate that the typical human has to eat around one egg every other day or so. Coupled with a global population of $\approx 7 \cdot 10^9$ people on the planet, and 365 days per year, we can compute an estimated yearly mass of consumed eggs to be $\approx 5 \cdot 10^{10}$ kg or $\approx 50\ \text{Mt} \cdot \text{year}^{-1}$. This estimate, schematized in the top-panel of Fig. 2 (A) is well within a factor of two of the actual mass produced per year. Over the 2010-2018 year period of data collected by the FAO, there were on average ≈ 65 Mt of eggs produced per year. This, for reference, corresponds to $\sim 10^{12}$ eggs or ~ 100 billion cartons of eggs.

How does this compare to poultry, the other potential fate of chicken? Again relying on the work of Eshel et al. (2014), poultry is responsible for $\approx 5\%$ of the typical caloric input or ≈ 100 kcal per day. The caloric density of poultry meat depends on the type of cut (dark meat or light meat), but for purposes we will make the approximation that it is similar to that of eggs or $\approx 1\ \text{kcal} \cdot \text{g}^{-1}$. This means that per day, our typical person must consume ≈ 100 g or poultry per day. Following the procedure shown in the bottom panel of Fig. 2 (A), we arrive at an estimate of $\sim 3 \sim 10^{11}$ kg or ~ 300 Mt per year. This number is within a factor of a few of the 2010-2018 FAO average of ~ 1000 Mt per year, a difference reasonable considering our approximation of the typical diet be similar the Western diet.

These estimates represent a reasonable order-of-magnitude argument for the total mass of *consumed* egg and poultry. It it interesting that these numbers are closely aligned with the FAO measurements of the globally *produced* mass. The typical fraction of food lost due to waste (spoilage or plate-to-trashcan loss) is $\approx 20\%$ (Shepon et al., 2018), providing a somewhat reasonable estimate of our error or general uncertainty of these estimates.

How many animals are responsible for producing this rather incredible mass? While tempting, it is *not* a reasonable assumption to state that all chickens are the same. Typically, the breeds of chicken used to produce eggs have little-to-no overlap with the chicken breasts that decorate our grocery's coolers. Egg-producing chickens, colloquially termed "layer" chickens, typically live around 18 months and are able to begin laying eggs as early as four months of age. With a laying rate of ≈ 1 egg $\cdot$ day^{-1}, the high-yield layer chicken can produce ≈ 350 eggs $\cdot$ year^{-1} (Zaheer, 2015). We will, for the sake of convenience, that all chickens globally operate at this high-yield. Again assuming a typical egg mass of ≈ 50 g, we arrive at an estimate of $\approx 3 \times 10^9$ layer chickens needed to produce the estimated annual mass of eggs produced globally. This estimate is very close to the FAO observed average of $\approx 7 \times 10^9$ layer chickens per year. Given that our approximation of all chickens as high-yield, 300 egg per year producing varieties, we expect our value to be a mild underestimate of the measured value.

Meat-producing chicken, typically referred to as "broiler" chickens, have also been the targets of intense industrial breeding to maximize yield. This variety of chicken has a remarkably short life span of ≈ 6 weeks, during which time they can accumulate ≈ 4 kg of body mass, a remarkable increase from the ≈ 1 kg body mass of mature broiler chickens in the mid 1950's (Tallentire et al., 2016; Zuidhof et al., 2014). Of this body mass, $\approx 70\%$ is ultimately harvested (Kokoszyński and Bernacki, 2008) yielding around ≈ 3 kg of edible mass per broiler chicken. Combining this array of numbers, we can arrive at an estimate bottom panel of 2 of $\sim 10^{11}$ broiler chicken processed annually. Once again, this simple estimate is within a factor of a few of the FAO recorded number of $\approx 6 \cdot 10^{11}$ broiler chicken per year. This number dwarfs the number of layer chicken processed per year by nearly an order of magnitude, even though the difference in produced mass is only a factor of a few.

Thus, on average, approximately ≈ 150 Mt of chicken product is produced annual from ≈ 70 billion individuals. The latter value is larger than the standing population by a factor of ≈ 4. We can remedy this apparent disagreement by realizing that with a lifespan of $\approx \frac{1}{8}$ year, the standing population can be computed as

$$N_{\text{chicken}}^{\text{(standing pop)}} \approx \frac{70 \cdot 10^9 \text{chicken}}{\text{year}} \cdot \frac{1}{8} \text{year} \approx 10^{10} \text{chickens}, \tag{1}$$

which is comparable to the $\approx 20 \cdot 10^9$ individuals reported by the FAO and shown in Fig. 1.

Cattle With the population of chickens accounted for, we now turn our focus towards the next abundant member of livestock – cattle. Like chicken, cattle are responsible for two major components of our typical human diet, dairy and beef. The former includes milk which can be transformed into a variety of different foods such as cheese, butter, and curds, all of which make up $\approx 10\%$ of daily calories or ≈ 200 kcal. As everything begins as milk, we will attempt to estimate the total mass of cow milk produced annually.

Full-fat milk has a relatively low caloric density of ≈ 0.5 kcal$\cdot$g^{-1} ((2013), pp. 107). Thus, with ≈ 200 kcal$\cdot$day^{-1}, around ≈ 200 g of milk need to be consumed per person per day. It therefore follows that $\approx 10^{12}$ kg of milk are consumed globally per year. Similarly to our estimates for chicken product, our estimate for milk production is within a factor of a few from the measured yearly production of $\approx 6 \cdot 10^{1}1$ kg$\cdot$year^{-1} Fig. 3.

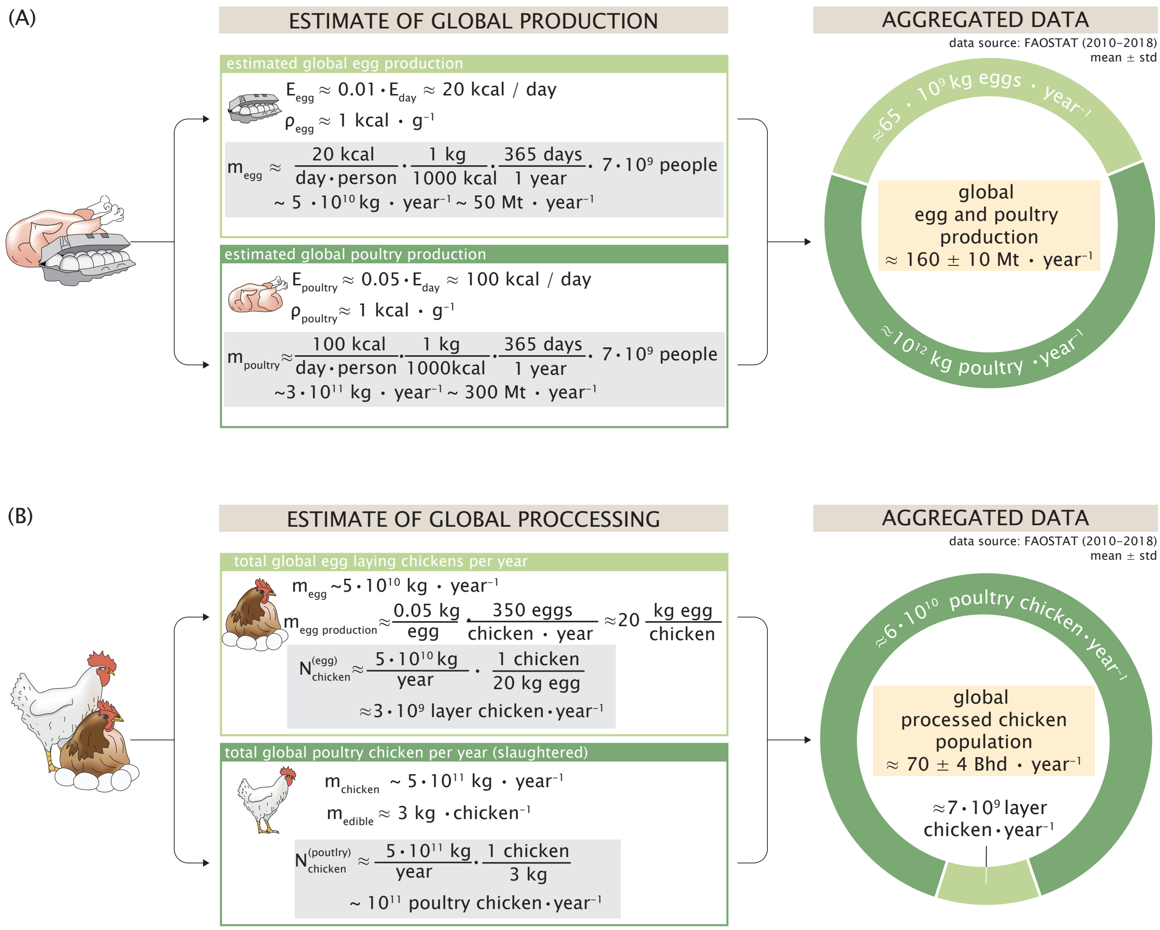

Fig. 2: **Sizing up global mass of consumed chicken product and processed population.** (A) Estimate for the amount of eggs (top panel) and poultry (bottom panel) consumed per year. The daily caloric intake of the average human is assumed to be ≈ 2000 kcal $\cdot$ day^{-1}. (B) Estimate for the number of processed chickens per year to produce mass of egg and poultry from estimates in (A). Donut charts in right-hand side show the average distribution of chicken product (top) and processed chicken population (bottom) from the years 2010-2018 as recorded in the FAOSTAT data base. Reported values for total mass and processed population is reported as the mean and standard deviation of the 2010-2018 measurements.

Beef, like milk, also constitutes $\approx 10\%$ of daily calories in our archetypal diet. However, beef is significantly more calorie dense than milk with caloric density of ≈ 3 kcal$\cdot$g^{-1}. Thus, to intake ≈ 200 kcal$\cdot$day^{-1}, our typical human has to consume on the order of 65 g of beef. As outlined in Fig. 3 (A), expanding this to the $\approx 7 \cdot 10^9$ people on the planet results in $\sim 10^1 1$ kg or ~ 100 Mt a year. This estimate is within a factor of a few of the FAO measurement of ≈ 60 Mt$\cdot$year^{-1}.

How many cattle does it take to yield this amount of milk and beef? Like chicken, cattle come in two varieties with dairy cattle producing milk and beef cattle producing, well, beef. As each variety has been intensively bread to prioritize milk or beef production, there is effectively zero overlap between the producing populations. The exception is that dairy cattle, when exhausted of their milk producing capacity, will be slaughtered for low-quality beef products or high-protein feed for other livestock. For simplicity, we will assume that the contribution of dairy cattle to yearly beef production is negligible.

Dairy cattle are remarkable in their ability to produce milk. In industrial settings, a high-yield dairy cow can produce around 30 L of milk per day or ≈ 30 kg. This is produced over a maximum of ≈ 10 months with at least 60-days of a rest period before lactation can resume. Thus, over a ≈ 300 day lactation season, a single cow can produce $\approx 10^4$ kg of milk (Bello et al. (2012) Figure 1) – an order of magnitude above what is typically produced in non-industrial conditions (Bello et al., 2012). With $\approx 10^{12}$ kg milk $\cdot$year^{-1}, on the order of 10^8 dairy cattle are needed per year, a value within a factor of a few of the FAO measurement of $3 \cdot 10^8$.

What about for beef? Beef cattle have been bred to be enormous, with the typical angus beef cattle being on the order of ≈ 500 - 1000 kg. This so-called "on-the-hoof" mass does not completely edible. After slaughter, the carcass is stripped of non-edible components resulting in a net edible mass of ≈ 200 kg of beef per cow (Division). Therefore $\approx 5 \cdot 10^8$ beef cattle are processed each year for beef, within a factor of two from the FAO measurement of $\approx 3 \cdot 10^8$.

In total, ≈ 700 Mt of beef product is produced globally using ≈ 550 million cattle. In contrast to the utilized chicken population, this number is a factor of ≈ 3 *below* the FAO reported number for the standing cattle population. This again is due to the matter of lifespan. Cattle, whether beef or dairy, have a life span on the order of ≈ 2 - 3 years from birth to culling. Thus, between 2 and 3 times the global processed population will need to be reared per year to meet demand, meaning the standing population can be approximated as

$$N_{\text{cattle}}^{\text{standing pop.}} \approx \frac{5.5 \cdot 10^8 \text{ cattle}}{\text{year}} \cdot 3 \,\text{year} \approx 1.5 \cdot 10^9 \text{cattle}, \tag{2}$$

which is inline with the $\approx 2 \cdot 10^8$ cattle under global agricultural maintenance as reported by the FAO, shown in Fig. 1.

Swine

The Magnitude of Annual Livestock Processing

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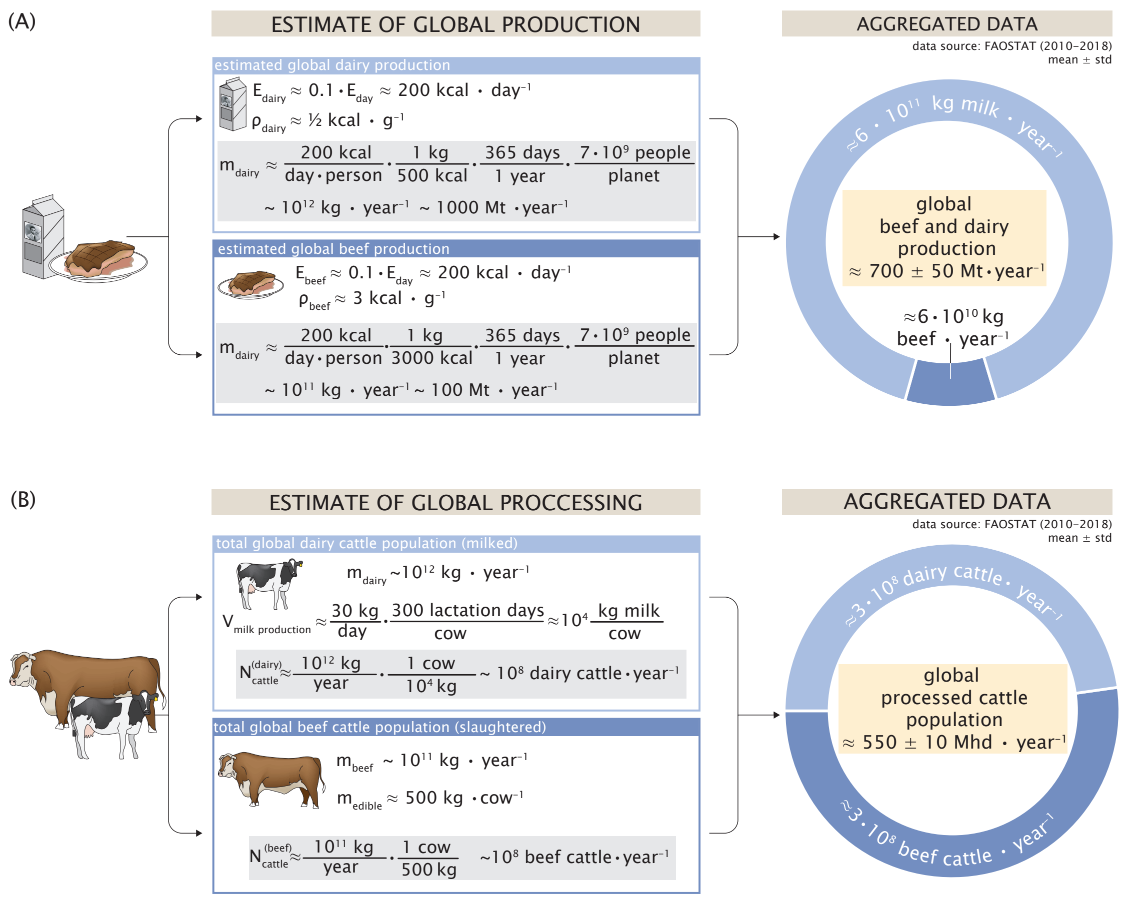

Fig. 3: **Sizing up global mass of consumed cow product and processed population.** (A) Estimate for the amount of milk (top panel) and beef (bottom panel) consumed per year. The daily caloric intake of the average human is assumed to be ≈ 2000 kcal $\cdot$ day^{-1}. (B) Estimate for the number of processed cattle per year to produce mass of milk and dairy from estimates in (A). Donut charts in right-hand side show the average distribution of cattle product (top) and processed cattle population (bottom) from the years 2010-2018 as recorded in the FAOSTAT data base. Reported values for total mass and processed population is reported as the mean and standard deviation of the 2010-2018 measurements.

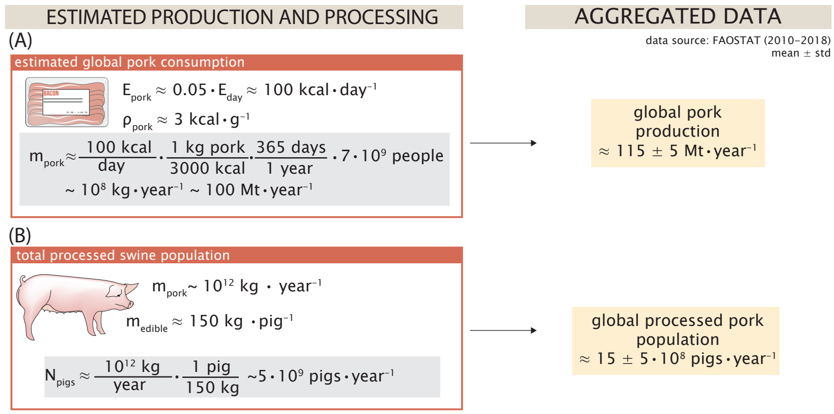

Fig. 4: **Sizing up global mass of consumed pork product and processed population.** (A) Estimate for the mass of pork product produced. The daily caloric intake of the average human is assumed to be ≈ 2000 kcal · day^{-1}. (B) Estimate for the number pigs processed per year given pork product mass estimate given in (A). Text-boxes on right-hand side of (A) and (B) correspond to the mean and standard deviation of the reported measurements in the FAOSTAT data base for the years 2010-2018.

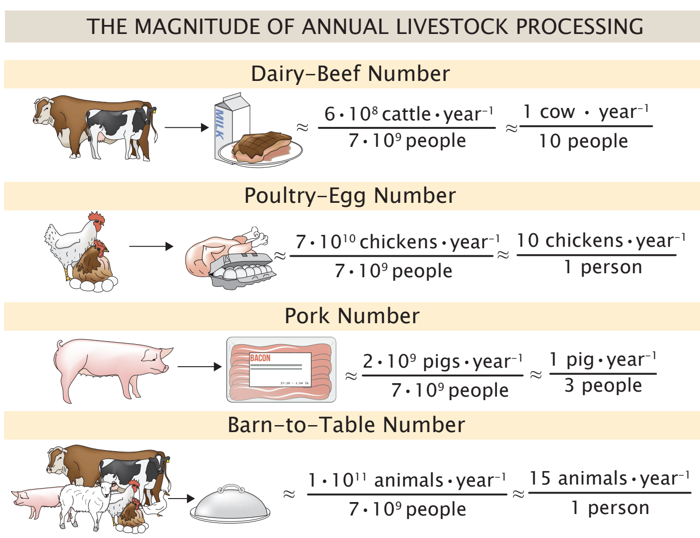

Fig. 5: **Rules-of-thumb for the annual flux of processed animals per capita.** Values provided in the number estimates correspond to the approximate averages of the reported producing population for each product from the FAOSTAT database for years 2010-2018. The "Farm-To-Table" number considers estimate of the number of animals processed for all meat, milk, and egg production across several animal categories as calculated by the FAO.

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Division, F.S. How Much Meat? (Not all of the cow makes it to the table. On average, a 1,000 pound steer will only weigh approximately 61% of it's live weight once it makes it to the rail. This approximate 39% loss during the slaughter and dress- ing procedure is a result of the ani- mal being bled and the hide, head, hooves, viscera, lungs and heart be- ing removed. The remaining 61% is often referred to as the "Hanging Weight" or the weight "On the Rail". But, the loss doesn't stop there. Once the carcass is on the rail it begins to leach moisture (shrink) which accounts for addi- tional weight loss. This along with the fat and bone removed during the cutting account for an additional 18% loss. In summary , a steer weighing 1, 000 pounds on the hoof will average around 430 pounds of retail cuts (steaks, roasts, ground beef, stew beef, etc.).).

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