How Many Acres of Potatoes Does a Society Need? Using Food and Historical Claims in an Energy Context

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One of the main difficulties in a class on sources of energy and social policy is the wide variety of units used by different technologists (British thermal units, barrels of oil, quads, kilowatt-hours, etc.). As every student eats, I think some of this confusion can be resolved by starting and grounding the class with a discussion of food and food production. A general historical outline for this introduction is provided with two interesting historical cultural examples, Tenochtitlan and the Irish Potato Famine. Science and social policy classes are full of bespoke units and involve many different contexts. Starting the class with a discussion of food energy is a nice way for everyone to start with the same context. In addition, discussion of food energy can lead to interesting historical claims.

Historical food energy production figures

When the United States entered World War I, one of the problems it faced was logistics. How much food do you need to ship across the Atlantic to feed a million soldiers? That early work in nutrition led to the 3000-Calorie diet many people remember from health education class. A reminder about "Calorie" (uppercase) vs. "calorie" (lowercase) units: 1 Calorie = 1 kilocalorie = 1 kcal = 1000 calories, and a dietitian might build a 3000-kcal diet for a 20-year-old basketball player. One calorie = 0.001 kcal, the amount of energy typically needed to heat 1 g of water by 1°C.

One feature of the modern "homesteading" culture is the idea that a person should be able to move to the country and grow all their own food. Learning that farming labor is *skilled* labor can be brutal and disheartening. Eating 3000 kcal each day means planting, weeding, harvesting, and storing more than 1,000,000 kcal each year.[1] Where will those Calories come from? Is your backyard enough to homestead in the suburbs?[2]

At some point between 1920 and 1950, US chemical manufacturers realized that in the post-war period, they could repurpose processes developed for manufacturing munitions and chemical warfare agents to produce chemicals that would kill insects and increase the nitrogen levels in the soil. As Figs. 1 and 2 show, the epoch of "Better Living Through Chemistry" produced a dramatic increase in per-acre yields across all commodity food crops, particularly corn and potatoes.

If you're discussing backyard Calorie production, it isn't reasonable to use modern yield estimates for planning. "Roundup Ready" corn, soybean, and sugar beet seeds are not readily available to the public, nobody wants to put on a respirator to apply atrazine 10 ft from the kids' swing set, and the edge effects from deer and insects are much smaller on a 640-acre field than they are in a community garden allotment.

In 1917, the United States Department of Agriculture (USDA) published a pamphlet[8] giving detailed per-acre Calorie estimates a farmer might expect from a given crop—these mea-
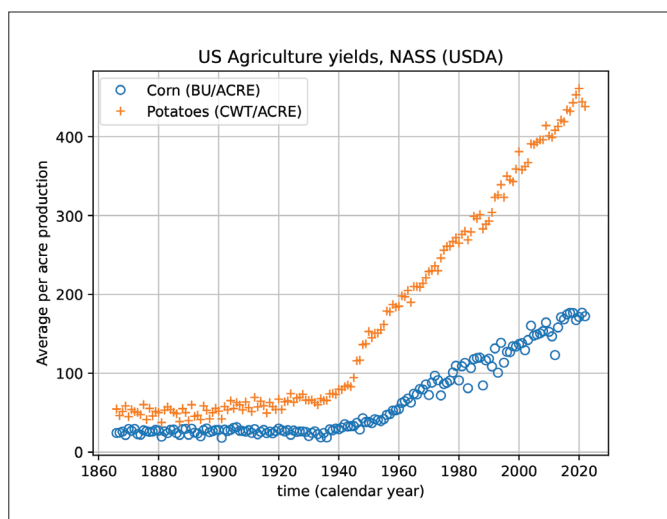

Fig. 1. Historical average staple crop production of corn (maize) and (Irish) potatoes in the United States. The data comes from the National Agricultural Statistics Service,[3] details online.[4] Note the dramatic increase in production after World War II. Data is given in harvest units, bushels (BU) per acre (1 bushel ≈ 35 L, weighing 56 lb) for field corn and hundredweight (CWT) for potatoes. By mass, corn is about 4.5 times more calorie dense than potatoes, which results in a nearly equal kcal/acre values for both crops in Fig. 2.
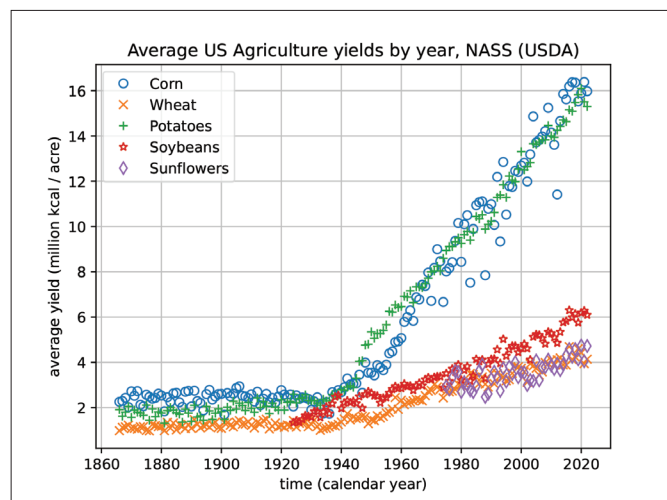

Fig. 2. This figure uses data identical to that in Fig. 1; however, the vertical axis has been scaled to millions of kilocalories produced per acre, and additional crops have been included. The dramatic increase in production after World War II is still visible, and if you like, the vertical axis could be read as "human beings fed per acre," as a person needs about 1,000,000 kcal of food each year. Details and conversions are given in Refs. 4 and 5. The idea for this plot came from an online blog.[6] It would be interesting to know if there are patterns of scaling among vegetable families (grains, legumes, tubers, etc.) in the same way that there are family classifications for the minimal energy required for transport.[7]

surements were directly related to the WWI food production problem mentioned earlier. An excerpt from this pamphlet is shown in Fig. 3.

The pamphlet data came from prewar, prechemical agriculture, and the yields cited were produced with horses, manure, lime, and large families full of children. If you want to be self-sufficient, the yield numbers in Fig. 3 are probably a reasonable upper bound on what's possible.

Using this data and assuming a family of four requires 3000 kcal/person each day, we can sketch out the land area needed for suburban self-sufficiency. Is 3000 kcal/person-day accurate for a family? For soldiers or active athletes it is, but 2000 kcal is the USDA reference for an "average adult," e.g., the author, in his 40s, and 1000–1200 kcal for a senior age (>60) female. However, weeding the garden all day is physically taxing, mice will probably eat some of the potatoes, and 3000 is a nice round number, so that's what I'm using.

Fig. 3. A table from a USDA-produced pamphlet, printed in 1917.

If we overestimate and produce food for the entire year, the family will need about 4.4×10^6 kcal:

$$4 \text{ people} \cdot \frac{3000 \text{ kcal}}{\text{person} \cdot \text{d}} \cdot \frac{365 \text{ d}}{\text{yr}} \approx 4.4 \times 10^6 \text{ kcal.} \quad (1)$$

From Fig. 3, we can estimate 1.9×10^6 kcal per acre of potato production.

$$\frac{4.4 \times 10^6 \text{ kcal}}{\text{family}} \cdot \frac{1 \text{ acre}}{1.9 \times 10^6 \text{ kcal}} \approx 2.3 \text{ acres.} \quad (2)$$

What does the answer of 2.3 acres mean? A university's 91 m × 49 m football field has an area of about 1.1 acres, so you could say that a football field, planted in potatoes, will probably feed a family through the winter.[9] Can a person enjoy the benefits of urban living and grow all their own

food? The population density of New Jersey is 1263 people/mi$^2 \approx 1.97$ people/acre, and our four-person family needs 2.3 acres for their all-potato winter.[9] Unless the social model is one of a country dacha or an endless suburb with no duplexes or apartment buildings, urban living and food self-sufficiency seem mutually exclusive.

Of course, these simple estimates assume there is sufficient labor to work in the fields, and that food can be efficiently stored. From an ethical perspective, beyond simple logistics, can people afford to grow their own food, or are they economically or socially excluded?

More emotionally charged conversations can be had about converting the United States to all organic agriculture, which, for corn, typically has a yield penalty of about 20–40 bu/acre compared to conventional production. The 1917 data isn't directly applicable, but it relates. At 180 bu/acre, conventional corn requires ~24 million acres (half of Wisconsin, or all of Indiana) to feed the US population (350 million people) corn for a year. The remainder of the corn belt can be devoted to animal feed, ethanol, and export. If the corn belt were devoted to producing organic corn at lower yield,[10] we probably wouldn't starve, but cheap meat and ethanol vehicle fuel would likely disappear.

Example: How big could Tenochtitlan have been?

While a discussion of food energy is certainly useful in an introductory physics context, more powerful ethical arguments can be made. Consider the pre-Colombian capital of the Aztec Empire, Tenochtitlan, now known as Mexico City. Tenochtitlan was built on and around an endorheic lake, Texcoco. Crops were grown in shallow parts of the lake via chinampas[11]—"floating" patches of decaying vegetation and soil. Given the proximity to water and decaying vegetation, these fields were very fertile,[12,13] and some continue to be used in the present day. Chinampas are still visible in satellite imagery. See, for example, latitude 19.268°, longitude −99.087°.

Estimates of Tenochtitlan's population in 1500CE vary widely, from 40,000[14] to more than 400,000 inhabitants,[15] comparable in size to Paris at that time. These estimates come from oral and written records, and estimates of archaeological building density and land area. While cannibalism was part of Aztec religious ritual and practice,[16] the staple Calorie sources for the Aztecs were corn, beans, quinoa, and amaranth.

Few, if any, Native American cultures made use of draft animals for food or power before the Colombian Exchange. This means that the food that fed Tenochtitlan must have been brought to the city center by foot or canoe. How much land must have been devoted to chinampas to feed the population, or conversely, how many people could be supported by the land within walking or paddling distance from the city center?

A 1964 paper in *Scientific American*[12] gives a general outline of the chinampas near Tenochtitlan in 1500CE. This map, shown in Fig. 4, seems to be the basis for the similar figure in Wikipedia.[17] Descriptions of chinampa agriculture indicate

that as many as seven successive crops could be grown and harvested from the same plot of soil each year, two of which could be maize (corn). This is truly amazing productivity, given that in the Midwestern United States, corn is normally grown, at most, every other year because of its extreme nutrient demands on the soil.

There are many ways to approach this estimation problem. We could assume a Tenochtitlan population of 100,000 people has a 3000 kcal/day diet that comes completely from corn. If corn's density and nutritional content haven't changed in the four centuries preceding the 1917 data in Fig. 3, we could assume 1 lb of corn contains ~1594 kcal of food energy.

How much crop land was available? ImageJ[18] is an image analysis tool that is widely used in biological sciences for, e.g., counting cells, measuring organelle area, and other similar quantitative measurements that might come from a microscope slide. I used ImageJ to measure the area devoted to chinampas in Fig. 4 to be about 16,000 acres (for details, see Ref. 5, Appendix B). With these assumptions, we could equate the corn energy production from chinampas with the population's yearly food need. Note that in this version of the story, P, the corn productivity in bushels per acre, is treated as an unknown variable.

$$\text{Food Production} = \text{Population Requirement}, \quad (3)$$

$$16{,}000 \text{ acres} \cdot \frac{2 \text{ corn crops}}{\text{yr}} \cdot P \frac{\text{bu of corn}}{\text{acre}} \quad (4)$$

$$= 100{,}000 \text{ people} \cdot \frac{3000 \text{ kcal}}{\text{person} \cdot \text{d}} \cdot \frac{365 \text{ d}}{\text{yr}} \cdot \frac{1 \text{ lb corn}}{1594 \text{ kcal}} \cdot \frac{1 \text{ bu}}{56 \text{ lb}},$$

$$P \approx 38 \text{ bu/acre}. \quad (5)$$

This crop productivity is in remarkable agreement with the 1917 USDA yields, 35 bu/acre, which seems to validate the assumed 100,000-person population of Tenochtitlan, and certainly invalidates the claim that Aztec cannibalism
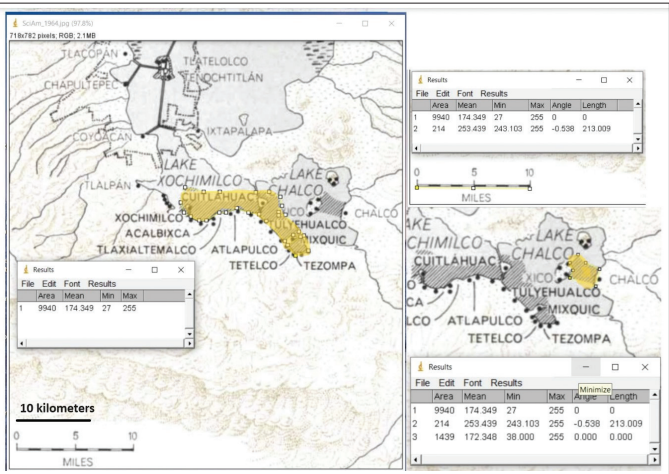

Fig. 4. Three screen captures showing chinampa areas near Tenochtitlan and the calibration stick used to convert area (in pixels) into square miles. The image being analyzed is available online.[12]

was necessary because of starvation.[19] Some references[16] describe an extensive tribute system that Aztec government required of its subjects, which certainly would have been necessary to support populations on the upper end of historical estimates.[15] An interesting follow-up question might be to expand the analysis presented with a range of crop productivity figures, populations, and daily caloric needs to see how it compares with the population estimates in the literature.

Example: Was the Irish Potato Famine a natural disaster?

In contrast to native cultures of the Americas, Ireland's population boomed with the Colombian Exchange and the introduction of the potato.[20,21] Figure 5 shows this dramatic growth in the island's population from about 1700 onward. There's never just one reason for historical events, but unlike grains, potatoes thrived in Ireland's cool damp climate. Potatoes, kale, and milk form a nutritionally complete diet that greatly reduced hunger-related mortality among the poor working class in Ireland. While there were numerous potato crop failures in 1700–1800s Ireland, only one had a significant effect on population. The crop failure and famine of 1740–1741 was similar in agricultural scale to the great famine of 1845–1852, but there's little evidence of a 1740 famine in the Fig. 5 population data. Both famines were precipitated by poor weather, but an important difference was that in 1740, Ireland was a sovereign state, but by 1845, the island was effectively an economic colony of the British Empire.[20]

As the story goes, the two main commodity crops in Ireland were potatoes (for humans) and oats, which as horse feed, were something like gasoline in today's economy. A sovereign government can halt the export of food to feed English horses, which is what happened in 1741 (and 1782). The grain was diverted back as relief to starving people in Ireland,
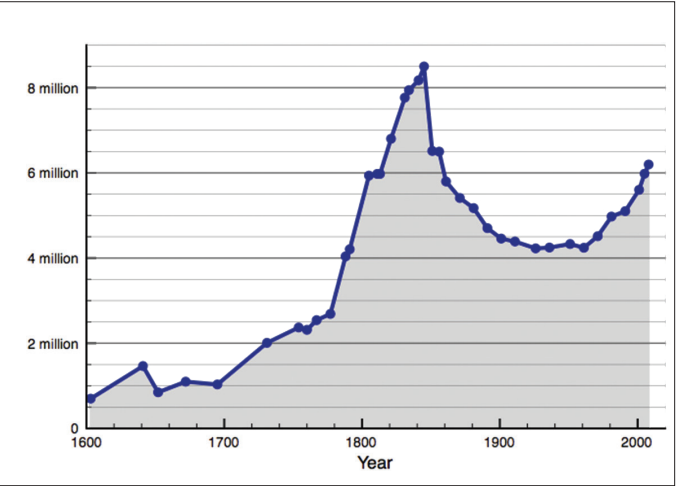

Fig. 5. The population of Ireland over time (reproduced from Ref. 22 under a CC BY-SA 3.0 license). Potatoes, kale, and milk were part of an amazing population boom. Note that there were several weather-related "potato" famines in Ireland, the most drastic in about 1740 and 1850. Government policy response to these famines could explain the drastic difference in subsequent population following each. The population of Ireland finally re-reached its 1851 peak in 2021.[23]

reducing the famine's mortality. However, by 1845, most Irish farmland was economically controlled by foreign (English) markets, and grain traders typically refused to divert oats (horse feed) as famine relief for the sake of their investment income.

This inflammatory claim, which is certainly a simplified version of history, serves as a useful evaluation example for students. Specifically, in years that the potato crop failed because of weather or late blight, could the amount of oats produced (and exported) have fed the Irish population? More broadly, was the Great Famine due to weather and disease, natural causes that "we can't do anything about," or was the depth of the tragedy a result of political choices?

Some estimates follow: Ireland's population in 1845 was about 8.5 million people. The island has an area of about 84,400 km^2, and you might estimate that 64% of the land (54,000 km^2) is arable for agriculture.[24] It seems reasonable to use the 1917 productivity (Fig. 3) to make calculations for Ireland in 1845. As a reminder, in 1917, potatoes produced 1.908×10^6 kcal/acre and oats 1.254×10^6 kcal/acre. With students, evaluation of the claim could be approached as a series of questions:

How much food does the island need?

$$\text{Food needed per year} = 8.5 \times 10^6 \text{ people} \cdot \frac{3000 \text{ kcal}}{\text{person} \cdot \text{d}} \cdot \frac{365 \text{ d}}{\text{yr}} \approx 9.3 \times 10^{12} \text{ kcal}. \quad (6)$$

How much land area, sown in potatoes, would produce this food?

$$9.3 \times 10^{12} \text{ kcal} \Big/ \left(1.908 \times 10^6 \frac{\text{kcal}}{\text{acre}}\right) = 4.87 \times 10^6 \text{ acres} \approx 19,700 \text{ km}^2. \quad (7)$$

How much land area, sown in oats, would produce this food?

$$9.3 \times 10^{12} \text{ kcal} \Big/ \left(1.254 \times 10^6 \frac{\text{kcal}}{\text{acre}}\right) = 7.41 \times 10^6 \text{ acres} \approx 30,000 \text{ km}^2. \quad [25] \quad (8)$$

Summed, 49,700 km^2, these two areas devoted to oats and potatoes are roughly equivalent to the amount of arable land estimated above for Ireland, 54,000 km^2.[24] What do the numbers mean? Did there have to be a famine? If the entire potato crop failed because of late blight, there would likely have been enough oats to feed the population a 2000-kcal ration with leftover oats to spare. Like the Holodomor or the Great Leap Forward, the numbers suggest that large-scale suffering wasn't simply a natural disaster, but rather a "human disaster" that resulted at least in part from economic and government policy.[26,27]

Energy units and the class context

There are about 4.2 J in a single calorie, and a joule shows up all over introductory physics. However, if you need to buy a new home furnace, the sales brochure might advertise that it can deliver 100,000 BTUs of heat each hour. What's a BTU? Enough energy to heat a pound of water by 1°F. Of course, heat pumps are far more efficient than simply oxidizing methane or propane, but they consume kilowatt-hours (kWh) of electricity, not BTUs. What's a kilowatt-hour? Run a 1000-W toaster for an hour and you'll have pulled 1 kWh

off the grid; it will cost you about $0.13 in Minnesota. If you decide to put solar panels in your backyard, they will probably collect about 10% of the 3.5 kWh the Sun delivers to each square meter of your lawn (in Minnesota) each day.

As the last paragraph illustrates, a frustratingly large number of different units of measurement appear in an energy class. At Winona State, this 3-credit class[28,29] fulfills a "Science and Social Policy" general education requirement and is taken by students from across the university. Many college majors don't require a math class beyond algebra or introductory statistics, and the population is largely math-averse. You could jokingly say that one of the main things students learn in the class is unit conversion, but it isn't far off. Nearly every field finds energy a useful representation, and every profession has their own set of units and terminology most suited for quick calculation. Would a medical lab scientist talk about the fractional acre-foot of urine needed to test kidney function? No, but someone in the central valley of California would certainly care about the acre-feet of water necessary to grow almonds!

Everyone eats, maybe not 3000 kcal per day, but at least something. When I teach our energy class, which focuses on the way our society turns solar, nuclear, and fossil energy into usable electrical energy and vehicle fuel,[28,29] I spend a few weeks talking about food energy before all other types—a summary of that introduction is given online.[5] While food production is not central to climate change and wars over oil, food is essential in a way that diesel and gasoline are not. Vehicle fuel makes modern life possible, but we could live, unpleasantly, without it. We can't live without fats and protein.

Conclusion

A class about energy and social policy and the author has hardly mentioned climate change, coal, or solar panels! What is he thinking?

How many tons of carbon does your car release in a year? How many shiploads of iron oxide will we have to dump into the ocean for phytoplankton to eat up the equivalent amount of carbon? Nearly every question in a class like this is informed by numerical calculation, and numerical literacy is important! If you're going to have success talking about numerical calculations, you might as well start with examples that everyone can relate to, and everyone eats! Along the way, you might find fascinating historical questions to investigate.

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