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U.S. Potential of Sustainable Backyard Distributed Animal and Plant Protein Production During & After Pandemics

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Abstract: To safeguard against meat supply shortages during pandemics or other catastrophes, this study analyzed the potential to provide the average household's entire protein consumption using either soybean production or distributed meat production at the household level in the U.S. with: 1) pasture-fed rabbits, 2) pellet and hay-fed rabbits, or 3) pellet-fed chickens. Only using the average backyard resources, soybean cultivation can provide 80%-160% of household protein and 0%-50% of a household's protein needs can be provided by pasture-fed rabbits using only the yard grass as feed. If external supplementation of feed is available, raising 52 chickens while also harvesting the concomitant eggs or alternately 107 grain-fed rabbits can meet 100% of an average household's protein requirements. These results show that resilience to future pandemics and challenges associated with growing meat demands can be incrementally addressed through backyard distributed protein production. Backyard production of chicken meat, eggs, and rabbit meat reduces environmental costs of protein due to savings in production, transportation, and refrigeration of meat products and even more so with soybeans. Generally, distributed production of protein was found to be economically competitive with centralized production of meat if distributed labor costs were ignored.

Keywords: food security; global catastrophic risk; resilience; pandemic; existential risk; COVID-19; soybeans; agriculture; chickens; rabbits; distributed production

1. Introduction

It is well-established that pandemics stress critical infrastructures and decision makers normally focus on hospitals and medical facilities [1–5]. This was again observed for the coronavirus disease 2019 (COVID-19) pandemic, which overwhelmed medical infrastructure at the regional level [6,7]. Food and agricultural infrastructures can also be challenged by pandemics for both humans [5,8] and animals [9,10]. During the COVID-19 pandemic, meat packing plants in particular were susceptible to rapid spread of the virus, as was observed in the U.S. [11,12], Canada [13], Spain [14], Ireland [15], Brazil [16], and Australia [17]. Meat packing plants have been some of the most highly concentrated producers of virus cases because of the low temperatures, close working conditions, strenuous physical demands of the job, and increased contaminated airflow within the plants [11,12]. One such meat packing plant in Triumph, Missouri reported 373 positive coronavirus cases [18]. Because more than eighty percent of the meat packing in the United States is conducted by only four companies [19,20], it is not difficult to imagine a partial shutdown of the meat packing industry during a viral

pandemic or another national crisis. This brings about many questions concerning the ability to produce enough protein for the nation to sustain a near total shutdown of the meat industry. Although it would be technically possible to provide all the protein necessary for the U.S. using plant materials [21,22], there is another option that may be more readily socially accepted in the U.S.: distributed production. During COVID-19, distributed production [23] was widespread to overcome supply shortages for personal protective equipment (PPE) [24-28], as well as medical equipment such as ventilators [29] and nasal swabs [3,31]. Conventional manufacturing normally occurs in a centralized factory with products being shipped to customers often over long distances, whereas, distributed manufacturing refers to manufacturing closer to the consumer (possibly even in the consumers' own homes) [26,32].

One practical option to safeguard against the challenges of a constrained meat industry is individual backyard rabbit and chicken farms or soybean production, which provides some food resilience for consumers in the case of strict lockdowns or a major food supply chain disruption. This idea appeared to be attractive to many people during COVID-19 pandemic as there were shortages of supplies of both animals and facilities (e.g. chicken coups) [33-37] and gardening supplies and seeds [38,39]. Those already involved in backyard meat production prove it is viable [40] - but is backyard protein production scalable to the national level? How much protein could be produced? How would it compare to the current system on sustainability metrics?

To answer these questions, this study analyzes the potential for three types of meat production at the household scale in the U.S.: 1) pasture-fed rabbits, 2) pellet and hay-fed rabbits, and 3) pellet-fed chickens, as well as backyard soybean production. For the first potential, the USDA Soil Survey is used to determine the potential rabbit yield per acre of different soil types, which is then quantified throughout the U.S. at the state level based on average yard sizes (and an additional method). For the second and third cases, these same yard sizes are used to determine meat yield assuming external feed is available. Lastly, the amount of protein that can be provided if the same surface area is used for soybean production is calculated. The results of this technical analysis are then evaluated in terms of percent protein of USDA requirements, economic viability, and environmental sustainability compared to the current meat systems. The results are discussed in the context of the potential for backyard meat production to aid in food supply resiliency in the face of pandemics and their aftermaths, as well as policies that would maximize benefits and minimize drawbacks to the approach.

2. Materials and Methods

The average United States (hereafter American) home has a yard measuring between 809 m² [41] and 1,010 m² [42]. The size of the average American yard is calculated by omitting people in communal living arrangements with no yards such as apartment buildings. While cattle and other large animals need over an acre of land to graze and roam [43], small-statured livestock including chicken and rabbits need considerably less space in comparison [44]. Considering this, three types of distributed meat production were evaluated: 1) free range rabbit, which only used the locally produced plant matter for feed; 2) pellet-fed rabbit, which used the locally produced plant matter in individual yards as well as external feed, and 3) chickens, which used only external feed, but produced both eggs and meat. Then the amount of protein that can be provided if the same surface area is used for soybean production is calculated.

2.1.1 Pasture-Fed Rabbits Method 1: Soil Survey

First, to examine the possibility of pasture-fed rabbit farming in backyards across America, the USDA Web Soil Survey [45] was used to determine the highest grass density in multiple regions and climates in the country. A map generated by Ricker in 2007 from the National Institute of Standards and Technology detailing different soil types was used to characterize states into major soil types and terrains. Alabama, Ohio, Vermont, Oregon, Kansas, and Wyoming were selected as representative states for their respective soil types. Selection was made based on the percentage of the state represented

by a soil type, the location of the state compared to other states with the same soil type, and data available within each state in the Web Soil Survey (sufficient data were not available for some states).

Representative cities were then selected within each state. Selection was made by using the city within the state with the median city size to determine what a typical town or living situation may be in that state. The cities (respective of the states listed above) of New Brockton (Alabama), Botkins (Ohio), Irasburg (Vermont), New Hope (Oregon), Fairview (Kansas), and Nordic (Wyoming) were used. The city addresses were then input into the Web Soil Survey and each area was examined for a primary forage type (either alfalfa hay, alfalfa, or pasture grass were used in this study) and the following equations were used to convert the vegetation data into the number of pasture-fed rabbits that could be supported per acre in each area during a growing season.

The total kg of wet alfalfa/acre/day (A) is given by:

$$A = \frac{\left(\frac{3.333}{0.00110231}\right)}{G} \quad [\text{kg/acre/day}] \quad (1)$$

Where x is the Imperial tons of dry alfalfa/acre/year and G is the number of days in a growing season. Dry alfalfa is the dry weight of the plant matter, which is multiplied by 3.333 to get wet weight assuming 33% dry matter [46].

The minimum and maximum values from equation (1) give a comprehensive range, which are then used to calculate the number of rabbits that can be supported in the average American backyard. These calculations assume that an adult rabbit needs 25 g of dry food per day per 1 kg body weight [47]. The weight of a rabbit is assumed to be 3.2 kg on the heavier rabbit size within the range of rabbit weights [48]. The water content of grass is also required and a range of 0.7-0.86 grams of water per grams of wet leaf is used [49]. The food mass required to feed an average rabbit for one day is given by:

$$F = \frac{wf}{P_{\text{dry}}} \quad [\text{kg}] \quad (2)$$

where F is the wet food mass required to feed an average (3.2 kg) rabbit for one day, w is the weight of an average rabbit, f is the number of kg of dry food an average rabbit requires per day per kg body weight (0.025 kg), and P_{dry} is the percent of dry matter in grass (0.14-0.3).

The lowest and highest values given for maximum mass wet grass per day during the growing season are calculated from the Web Soil Survey [45]. The range for average yard size is also used to obtain the mass in kg of grass produced per yard is given by:

$$k = (y_m \times 0.000247)S \quad [\text{kg}] \quad (3)$$

where k is the number of kg of wet grass produced per yard, y_m is the range of yard size in square meters, the numerical value of 0.000247 is the conversion factor to acres, and S is the value of kg wet grass produced per day from the Web Soil Survey.

With these two values from equations (2) and (3), the number of rabbits that can be fed continuously on an acre and in an average American backyard can be calculated by:

$$R_{\text{yard}} = \frac{k}{F} \quad [\text{rabbits/yard}] \quad (4)$$

Where R_{yard} is the number of rabbits fed continuously in an average American backyard and k and F are taken from equations 2 and 3.

To find the average number of rabbits sustained per acre, the following equation is used:

$$R_{\text{acre}} = \frac{S}{F} \quad [\text{rabbits/acre}] \quad (5)$$

Where R_{acre} is the number of rabbits fed continuously on an acre of grass, S is the range of values taken from the Web Soil Survey results, and F is from equation (2).

Certain soil types and states were not considered in this study because they would not facilitate the growth of enough vegetation to support the grazing of animals. Gray Desert Soils covering significant portions of the states of Nevada, Arizona, and New Mexico, and Nebraska Sand Hills covering Nebraska were discounted from the study. Discounting these states and their populations removes approximately 14.39 million people and 4.38% of the population of the United States.

Then using the acres available in each state and the expected yields in rabbits, the total annual pasture-fed rabbit production was calculated for the U.S. per year following:

$$t_{region} = R_{acre} * a \quad [\text{rabbits}] \quad (6)$$

where t_{region} is the number of rabbits sustained in a certain region/soil type, R_{acre} is the number of rabbits per acre given from the equation above (5), and a is the number of acres within the soil type.

When this has been performed for each region as denoted by soil type, those values can be added together to show how many rabbits can be raised with no supplemental food in the entire U.S. for one year, $R_{US-pasture}$, following equation (7).

$$R_{US-pasture} = \sum_{n=1}^T t_n \quad [\text{rabbits/year}] \quad (7)$$

Where n is the region and T is all of the regions (6 regions). Pasture-fed rabbits take 26-28 weeks to grow to the appropriate size for slaughter [48]. Using the information above, only one cohort of pasture-fed rabbits can be raised per year as a growing season for grass and alfalfa is stated as 180 days (about 26 weeks).

For pasture-fed rabbits the value for average yard size in the U.S. was used because rabbits grazing in the entire yard is the lowest maintenance option and the largest number of rabbits can be sustained this way. Implementing this option raises many other factors to consider such as predators invading rural yards and properly fenced in yards to prevent animal escape. According to the equations above, most American yards can sustain at least 1 rabbit fully free range for one year based on these conservative assumptions. A less-conservative method is based off an average grass growth and shown below.

2.1.2 Pasture-Fed Rabbits Method 2: Average growth

Another analysis of grass growth by the British Ecological Society showed much higher values of average grass growth across the United States. This study states that the net primary production in the temperate zone of lawns is approximately 1000-1700 g/m² per year dry matter [50]. Temperate grassland areas have growth measured to be 100-1500 g/m² per year of dry matter [50]. Tropical grasslands produce between 200 and 2000 g/m², and pasturelands have growth rates consistent with those of grasslands depending upon latitude [50].

In the United States, climate varies drastically throughout different states. The above ranges are averages to most accurately represent the climate in different areas of the U.S. The average value of growth is 1,083 g/m² (38.2 ounces/m²) dry per year, based on the lawn and temperate and tropical grassland averages in [50].

2.2. Pellet-Fed Rabbits Maximum

For pellet-fed rabbits and chickens, it was assumed that only half of the average yard size will be used for animal production since both of these animals require sizable houses or pens and do not need to roam a vast area to obtain their food. Average American yard size is 809-1,010 m² [41,42,51]. Using the range given above, there is an available caged animal farming area of 405-505 m². While this is the absolute maximum area that may be occupied for the purpose of this study, the number of animals able to be maintained in this area is not generally practical assuming that the person raising rabbits has career obligations other than rabbit farming full time.

Non-free-range rabbits require much less space than pasture-fed rabbits as their diet is not the determining factor of their living space. Depending on the size and weight of rabbit, desired quality of life for each animal, and method of raising, rabbits need anywhere from 0.14-3.70 m² of land to exercise

and live when they are hay and pellet fed [47,48,52,53]. This area is usually split between a caged area and a run. The large range of values is produced by sources omitting the run entirely. Wire cages are both recommended and discouraged as different breeders have different recommendations [47,53]. While a run is not essential for rabbit growth, omitting a run may lead to lower quality meat due to muscle atrophy [52].

For the purposes of this study, values given for the area of rabbit cages by Michigan State University Extension are used [53]. These values range from 0.14-0.46 m² per rabbit. It is also assumed that a run is required with an area of 2.5-3.0 m² per rabbit [47, 52].

With these values, total required area for one pellet-fed rabbit, A_{pr} is:

$$A_{pr} = A_c + A_{run} \quad [\text{m}^2] \quad (8)$$

Where A_{pr} equals the area required to house one pellet-fed rabbit, A_c is the cage size in m², and A_{run} is the desired run size per rabbit in m². With the above ranges, each rabbit is allotted 2.64-3.46 m² in total.

With these values, the number of rabbits that can be supported on half an American yard, $R_{pellets/yard}$ is calculated by the following equation:

$$R_{pellets/yard} = \frac{A_y/2}{A_{pr}} \quad [\text{rabbits}] \quad (9)$$

Where A_y is the area of the average American yard (809-1,010 m²), A_{pr} is defined above, and $R_{pellets/yard}$ is the number of pellet-fed rabbits that can be sustained at one time in half the average American yard. Pellet-fed rabbits only take 12 weeks to grow to appropriate size for slaughter [48] and since pellet-fed rabbits do not require grass as their main source of nutrition, 4 cycles of pellet-fed rabbits can be raised in a year if slaughtered at 12 weeks for each. Therefore, the total rabbits able to be harvested per acre per year in the U.S. is $4 \times R_{pellets/yard}$ and the total pellet fed rabbits is

$$R_{US-pellets} = 4 \times R_{pellets/yard} \times n_{yard} \quad [\text{rabbits/year}] \quad (10)$$

Where n_{yard} is the number of yards in the U.S.

2.3 Chickens Maximum

Industry stocking density for chickens is limited to less than 1 square foot per bird for all birds under 7 pounds [54]. This high density causes health problems such as leg deformities, broken bones, lack of social behavior with other birds, and can result in lower bodyweight and limited feed consumption [54,55]. To be considered free-range in industry, chickens need 0.30 m² (3.25 square feet) [54]. In industry, chickens are raised for meat or eggs, but not usually both [71].

Chickens raised only for meat (referred to as Broilers in industry) are slaughtered between 5 and 18 weeks [USDA, 54] whereas chickens raised for eggs are allowed to produce for as long as 72 weeks before being slaughtered [57,58]. For this study, it is assumed that chickens will be raised for one year (from hatchlings). Chickens begin producing eggs around 18 weeks of age and this study assumes they will be slaughtered at 1 year of age to maximize both meat quality and egg production.

Backyard chickens can be raised multiple different ways. Fully free-range chickens require supplemental feed and can either have space limitations or not. Chickens raised fully free-range have virtually unlimited space with a large coop to sleep in during the night that serves as protection from predators and the elements, and are fed kitchen scraps or some pellet feed to balance out a natural diet of insects, weeds, and other naturally occurring material [59]. Limited free-range raised chickens have only a coop and a small run to live in and are fed kitchen scraps and pellet feed for their entire diet [55]. Limited free-range chickens are most common in city or town settings and will be used for all calculations regarding obtainable protein from chicken meat and eggs because they are more accessible to most of the U.S. population.

The suggested density for a limited free-range chicken setup that can be applied most easily to backyard chicken production is no more than 13 birds per m² for the enclosed area with access to an open-air area with a density of no more than 1 bird per m² [55]. To remain conservative, each chicken is allotted approximately 1.08 m² (1.29 yards²) of space, which provides a square meter outside and 1/13th of a meter of enclosure. With this information, the following equation can be used to determine the maximum number of chickens that can fit in half of an average American yard:

$$C_{yard} = \frac{A_y/2}{1.08} \quad [\text{chickens}] \quad (11)$$

The value for number of chickens found with equation 11 is used to calculate the number of eggs available to each household per year. These calculations are performed assuming that meat chickens and egg producing chickens are the same and that chickens can produce eggs until they are slaughtered for meat. Chickens do not begin producing eggs until 18 weeks of life [71], meaning that their egg production (if raised from chicks that are hatched on day 1 of each year) lasts approximately 35 weeks.

2.4 Realistic Backyard Capacity for Pellet-Fed Rabbits and Chickens

Capacity for raising the maximum number of chickens or pellet-fed rabbits in most American backyards is unrealistic considering the time required to maintain that many animals. The equations below determine the number of animals required to produce 100% of the protein required to fulfill everyone in America for one year. These values are more than actually required as some protein is obtained from other food sources.

The average person consumes 51 g of protein per day (average of 56 g per day for the average sedentary man and 46 g per day for the average sedentary woman) which amounts to 18,615 g of protein per year per person [60]. This value is used for the calculations of percent of protein/year/household. The population of America is 328.2 million [61]. A household is defined by the U.S. Census Bureau as one or more people living in the same housing unit. There were 128.58 million households in the United States in 2019 [62]. By this definition, the average household contains 2.6 people.

To calculate the amount of protein required to feed the entire American population, the equation below is used:

$$P_T = 365 \times P \times p \quad [\text{grams}] \quad (12)$$

where P_T equals the total amount of protein required to sustain the U.S. population for one year, 365 is the number of days in a year, P is the U.S. population, and p is the number of grams of protein required per person per day.

P_T is used for calculations regarding number of chickens and number of pellet-fed rabbits. To calculate the number of chickens required to fulfill this entire protein need, equation 13 below is used.

$$C = \frac{P_T}{35 \times P_E \times A_{EPW} + P_C} \quad [\text{chickens}] \quad (13)$$

Where 35 is the number of weeks in a year that each chicken produces eggs, P_E , equal to 6.28, is the number of grams of protein in one egg, A_{EPW} , equal to the number of eggs produced in one week, C is the number of chickens to be raised in one year, and P_C , equal to 140.8, is the number of grams of protein in the meat of one chicken.

To calculate the number of eggs per year, E_{PY} , is:

$$E_{PY} = 35 \times A_{EPW} \times C \quad [\text{eggs per year}] \quad (14)$$

Where E_{PY} is equal to the number of eggs produced per year, 35 is the number of egg-producing weeks that each chicken has in one year, and C is the number of chickens being raised.

For rabbits, the average number of animals to be raised for 100% protein production is determined by:

$$R = \frac{P_T}{P_R} \quad [\text{rabbits}] \quad (15)$$

Where P_T is equal to 6.11×10^{12} as given by equation 15 and represents the total amount of protein required to sustain the country for one year, P_R , equal to 445.5, is the average of the range for protein value of one rabbit (297-594g), and R is the number of rabbits required to sustain the entire population for one year.

For both of the above equations, once the total number of animals required to sustain protein requirements is determined, that value is plugged in for A in the following equation to determine the number of animals per household required to meet this need.

$$A_{hh} = \frac{A}{128,580,000} \quad [\text{animals per household}] \quad (16)$$

Where A is the number of animals (rabbits or chickens) required to sustain the entire population's protein requirements for one year, 128,580,000 is the number of households in America, and A_{hh} is the number of animals to be raised per household.

To determine the total protein produced per household per year, A_{hh} should be multiplied by the given value for g protein per raw item.

To confirm the percent protein that will be provided by the identified number of animals, the following equation should be used.

$$P_p = \frac{A_{hh} \times 128,580,000}{P_T} \times 100 \quad [\text{percent protein}] \quad (17)$$

Where P_p represents the percent protein that is supplemented by a specific protein source. This equation should confirm that the value for rabbits per household correctly provides 100% of the protein requirements and shows the percentages of protein that are provided by chicken meat and eggs, respectively.

2.5 Backyard Soybean Production

Land requirements to produce animal protein is 6-17 times greater than for soy protein, demonstrating the potential for plant-based foods to offset natural resource demands and extensive land use [63]. Because of this, a situation in which backyards are used to grow soybeans is modeled below. Soybeans are extremely rich in protein and contain about 40% consumable protein by calories [64]. Since chicken meat is approximately 80% protein [65], it can be assumed that double the soybeans (in terms of grams of dry food) would need to be produced to supply equal protein. The half yard statistic of 405-505 m² is used for the calculations below. To grow a recommended number of soybeans to supplement into a normal diet, 4-8 soybean plants should be grown per household member which only provides a small percentage of necessary protein [66]. If soybeans are planted with a spacing of 3.5 plants per foot in rows that are separated by 15 inches, 122,000 plants per acre can be produced [67]. One acre is 4046 m², meaning that roughly 30 plants can be planted in 1 square meter of space and 12,100-15,200 plants could fit in half of the average backyard. Each plant typically produces 25-40 pods in a harvest (one season). This means that one backyard could produce between 304,000 and 606,000 pods per season.

100 soybean pods and the beans within the pods were massed on a digital scale (+/-0.1g) to obtain m_{pod} , the beans were counted and massed to obtain m_{bean} and the number of beans/pod ($n_{bean/pod}$), respectively. Commercial soybeans have a rated protein density (d_{soy}) of 9.46 g protein per 100g of wet soybeans [68]. Thus, the protein per pod, P_{pod} is:

$$P_{pod} = m_{bean} \times n_{bean/pod} \times d_{soy} \quad [\text{g protein per pod}] \quad (18)$$

Therefore, the protein per yard from soybeans $P_{soy/yard}$ is given by:

$$P_{soy/yard} = P_{pod} \times N_{pods/year/yard} \quad [\text{g soy protein per average yard/year}] \quad (19)$$

Finally, with humans needing 51g protein per day, the number of people soy production could support in the average yard per year is $P_{soy/yard}$ divided by 18.6kg.

2.6 Scaled Protein Production Potential

On average, Americans eat 88.7-107.7 grams (3.13-3.80 oz) of meat per day, which is 32,400-39,300 grams per year as shown by [69]:

$$A = G \times 365 \quad [\text{g/year}] \quad (20)$$

Where A is the number of grams of meat consumed per year and G is the number of grams of meat consumed per day.

To fuel this demand for meat products, the U.S. produces 52 billion pounds (24 billion kg) of meat for domestic consumption annually [69]. Most Americans are eating too much protein. From 2007 to 2010, 58% of the U.S. population was eating above the optimal amount of protein rich foods, most of which are meats [70]. As a result of these and other eating trends, more than two-thirds of adults and almost one-third of children in the U.S. are overweight or obese [70].

The three approaches to backyard meat production are compared to show the grams of protein from each of the respective protein sources, the required protein source per household per year to obtain up to 100% of the nation's required protein, protein mass per household per year, and the percent of protein that the source could provide per household per year. These are then compared to the number of people backyard soybean production could support.

2.7 Economics

According to the USDA, the average whole chicken costs \$1.28 per pound and the average live weight of a whole chicken is 8.2-11.7 lbs. [71]. Approximately 79% of live weight is retained from slaughter to sale or consumption of the bird. Thus, the typical weight of a processed chicken is 6.5-9.2 lbs. With these numbers, the average cost of one whole chicken ranges from \$8.32 to \$11.78. The average cost to raise one chicken per year with backyard costs is a culmination of costs of materials to build a coop, chicken feed, and of fertilized and sexed eggs.

If it is assumed that a chicken setup will be as basic as possible and the least expensive coop options are used, overall cost to raise any number of backyard chickens (3) is documented by the equations below:

$$C_{initial} = P_{chicken} \times N_{chickens} \text{ [dollars]} \quad (21)$$

$$C_{feedyear} = N_{chickens} \times N_{month} \times C_{chicken} \text{ [dollars]} \quad (22)$$

$$C_{overall} = C_{coop} + C_{feedyear} + C_{initial} \text{ [dollars]} \quad (23)$$

where $P_{chicken}$ is the price per chick (in this case 5), $N_{chickens}$ is the number of chickens to be raised (in this case 3), N_{months} is the number of months in a year, $C_{chicken}$ is the cost to feed one chicken for one year (in this case \$2), $C_{overall}$ is the overall cost of raising a number of chickens for one year, C_{coop} is the cost of coop materials, $C_{feedyear}$ is the cost of feeding a number of chickens for one year (each chicken requires approximately 2 dollars of feed every month), and $C_{initial}$ is the cost of purchasing 3 sexed eggs.

3. Results

3.1.1 Pasture-fed Rabbits Method 1

For all calculations, a growing season of 180 days was used. The results of the analysis for grass-fed rabbits are shown in Figure 1. In New Hope, Oregon and other similar areas with Mountainous Areas, ~90 rabbits can be sustained per acre in a growing season. In New Brockton, Alabama and other similar areas with Red and Yellow Soils, ~8 rabbits can be sustained per acre in a growing season. In Irasburg, Vermont and other similar areas with Podsol Soils, ~80 rabbits can be sustained per acre in a growing season. In Botkins, Ohio and other similar areas with Gray Brown Podsollic Soils, ~10 rabbits can be sustained per acre in a growing season. In Nordic, Wyoming and similar areas with Brown and Dark Brown Soils, ~70 rabbits can be sustained per acre in a growing season. In Fairview, Kansas and similar areas with Chernozem and Prairie Soils, ~3 rabbits can be sustained per acre in a growing season. Across soil types, one acre can sustain 3-90 rabbits, meaning a half yard can sustain 0-11 rabbits. This value would be greatly increased if rabbits were fed supplemental feed such as pellets or food scraps.

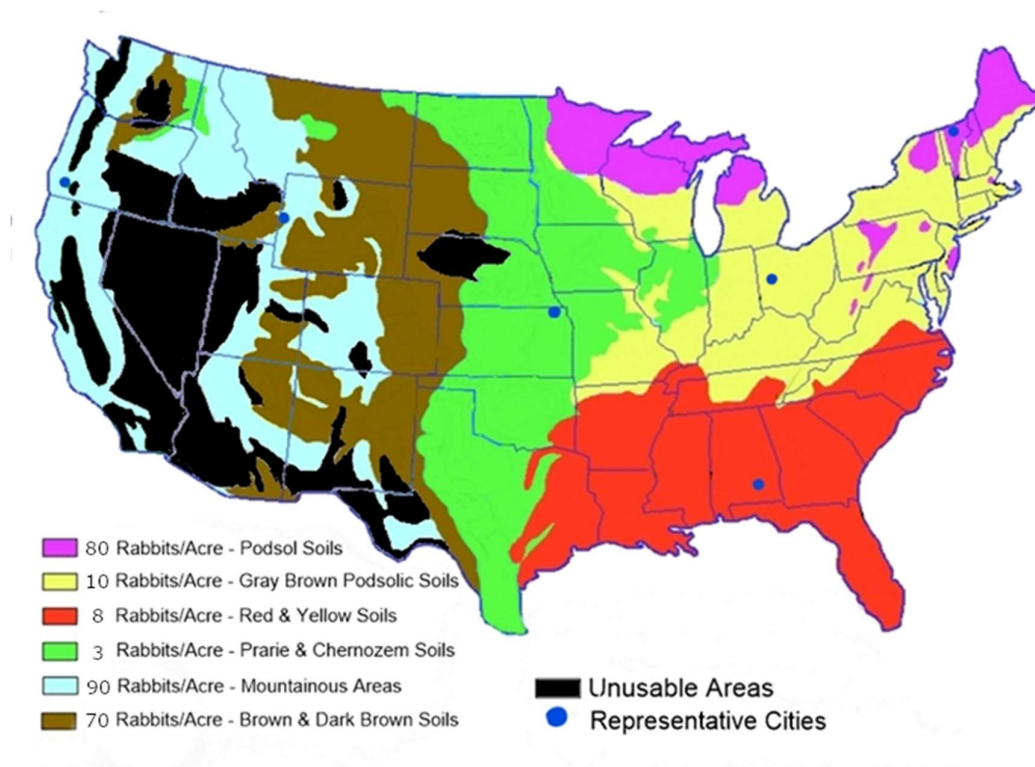


Figure 1. USA map with soil types and average production of rabbits per acre. Cities used for analysis via USDA Web Soil Survey are indicated. Areas considered unusable have little consistently growing vegetation and could sustain less than 1 rabbit per acre on average. Image adapted from [72].

3.1.2 Pasture-fed Rabbits Method 2

With the second method, average lawn grass production for the U.S. is 1.08 kg/m² in a year. Most adult pet rabbits need 25 g (0.025 kg) high fiber/low protein dry food per day per 1 kg body weight [150]. It is assumed 3.2 kg average weight of rabbits, corresponding to 0.08 kg dry feed per day. This is a highly conservative estimate for the mass of a rabbit. Considering these two values and the average yard size in the US (404-505 m²), an average yard can support, 30-40 rabbits during the growing season.

Another source [73] states that one rabbit requires approximately 46.5 m² (500 square feet) of space with non-rotational grazing. With this estimate, 8-10 rabbits can fit in the average American yard and eat only grass. These numbers are roughly between methods 1 and 2.

3.2 Pellet/Hay-Fed Rabbits

Young rabbits need to be fed a combination of hay, pellets, and fresh vegetables to have a balanced diet and stimulate growth [48, 74]. While the size of rabbit runs is not often factored into the area required to produce meat rabbits, rabbits' muscles will atrophy if they are not able to run daily and this will decrease the quality of meat obtained [52]. A small run is included in these calculations as described in the methods section above, but in general, the larger area a rabbit has to run, the healthier the rabbit will be. These values are a maximum allowed by space constraints and do not present a practical small-scale operation and should be used only if maximum meat production possible is required.

Depending on the rabbit, live weight can vary from 3-8 pounds and dress out to 2-4 pounds of usable meat [48]. Rabbit is an extremely lean meat with 100 grams of meat containing 33.02 grams of

protein but only 3.51 grams of fat [75]. As suggested by the USDA, a serving size of rabbit is 3 oz (85 g) which contains 28.1 grams of protein and 2.98 grams of fat [75].

Using the ranges given above and equation 9, the range for $R_{\text{pellets/yard}}$ equals 117-191 rabbits per yard at a time.

Pellet-fed rabbits also have a much more consistent rate of growth than pasture fed rabbits. It is documented that an approximate ratio of 3 pounds of dry feed to 1 pound of wet body weight is a desirable and healthy rate of growth for meat rabbits [76].

3.2.1 Pellet-Fed Rabbit Protein

It is assumed that pasture-fed rabbits and pellet-fed rabbits have the same nutritional value if raised until they are full grown. Since 100 g of rabbit meat has 33.02 g protein [75], one rabbit weighing 3-8 pounds (1.4-3.6 kg) live and dressing out to 2-4 pounds (0.9-1.8 kg) [48] has 297-594 g protein. Using equation 12, 1.37×10^{10} (13.7 billion) rabbits would need to be produced to fulfill the protein requirements for the entire country for one year.

Using the range calculated in section 2.2 and equation 7, the average American backyard can raise a maximum of 117-191 rabbits at one time and a maximum of 468-764 rabbits per year. This range does not consider cold, snow, or other inclement weather that may occur seasonally in different locations. This range also does not consider spacing of cages to allow for access, maintenance, and transfer of animals from their cage to the run. This range is impractical and is only used in this study as a cap for the practical calculations in later sections.

3.3 Pellet/Scrap-Fed Chickens

Industry bred chickens are raised for 6-9 weeks before slaughter [71]. However, free-range and backyard raised chickens are often intended to be slower grown and can take 9-12 weeks before growing to full size for slaughter [77]. Egg laying hens are not generally slaughtered until 72 weeks [57]. For the purposes of this study, the process will be to obtain freshly hatched chicks or eggs that hatch on or around the first of each year. Chickens will be raised and fed throughout the entire year, beginning to collect eggs when they are produced around 18 weeks. Chickens will be slaughtered for meat on the last day of the year.

This study examines chickens used for egg production for 1 year (35 weeks once chickens reach reproductive age) and slaughtered for meat, thus optimizing a chicken's egg production potential while limiting cost of feed and maintenance of raising a chicken for meat for longer than is necessary. Using the given range for American yard size and equation 9, 376-468 pellet/scrap-fed chickens can be supported on half of an average yard at a maximum. This value is unrealistic and is used as a cap for more realistic values calculated in the upcoming sections.

3.3.1 Chicken Protein

The meat of one chicken provides about 140.8 g protein [71]. Using the equations above, 52 chickens per household would need to be produced to provide 100% of the nation's protein requirements for one year.

3.4 Egg Protein

One fresh large egg has 6.28 g protein [71]. A source state that in winter months, a chicken will produce as few as 2 eggs per week [78], and another says an average chicken produces 200-250 eggs per year [79] which amounts to 4-5 eggs per week. Thus, the range of 2-5 eggs per week will be used as a more representative approach.

With the calculated value of 52 chickens per yard, 6,370 g of protein could be produced per year with egg production. For calculations in Table 1, the range of 2-5 eggs is used to calculate protein and percentages, yielding a large range that includes 100%. In Table 2, the range for egg production is averaged and a value of 3.5 eggs per week is used, leading to point values. With 52 chickens (using an average value of 3.5 eggs per week) and the equation below, 15% of the protein will be produced from meat and 84% of the protein will come from eggs.

3.4 Soy Protein

Soy production was found, as expected, to be a considerably more efficient use of backyard surface area. The value m_{bean} was experimentally found to be 0.58g, $n_{\text{bean/pod}}$ was 2.21, so P_{pod} was found to be 0.1225 g protein per pod from equation 18. Thus, the total soy protein per yard per year was found using equation 19 to range from 37.15kg and 74.21kg. It can be concluded that soybean production in the average American yard could support between two and four people for their protein needs throughout the year, which would thus put soy in the range of producing 100% of the protein needs for the average family.

3.5 Scaled Protein Production Potential

Table 1 uses equations 1-11 to show the number of each animal that would need to be produced to obtain up to 100% of the required protein to feed the entire U.S. for one year. Because of the ranges in the values for the protein sources, the percentages are also given as a range (except in the case of chickens).

Maximum space calculations were performed in equations 8-11 to determine the absolute maximum capacity of a yard. These values are not practical for most households and are used as a limit for the secondary calculations in equations 12-17. For egg calculations, a range for 2-5 eggs per week is used to account for different climates in different locations. Some places in America have cold or otherwise inclement weather for a majority of the year and would be on the low range, while the southern parts of America have temperate or warm weather year-round and will be on the higher end of the range.

Table 1. Protein Produced for Different Backyard Production Setups

	Pasture -Fed Rabbit	Pellet-Fed Rabbit	Chicken Meat	Eggs	Chicken Total	Soybeans
Protein per raw item (g)	297-594	297-594	141	6.28	N/A	0.12
Protein source/household/year	0-40	470-760	36-77	2,500- 13,000	N/A	300,000- 610,000
Total protein (kg/year/household)	0-20	140-450	5-11	16-85	21-96	37-74
Percent of protein requirement of US population met	0-50%	300- 1000%*	11-23%	33- 180%	44-203%	78-160%

* Note: backyard filled for rabbits but not for chickens

Table 2 details the number of animals required to produce 100% of a household's protein requirements for a year. The large range in percentage of protein/year for the U.S. population comes from the large range of protein values for many different breeds of meat rabbits. Because of the ranges in protein value, the range calculated for percent of protein per year for the U.S. population will contain 100% without including it in either bound. The number of chickens required to produce 100% of the protein/year/household is used to calculate protein for the number of eggs produced leading to an inflated value. The range for chickens is also expanded by the addition of a range for egg production.

In Table 1, the ranges have not been eliminated and thus the ranges for percent protein provided include 100 within the range but do not contain exactly 100% in either of the ends of their range. Table 2 averages out all ranges to give one value for protein sources, thus presenting singular values for number of animals required for exactly 100% of total protein to be supplemented.

Table 2. Protein Produced for Pellet-Fed Rabbits and Chickens with Averages of Ranges

	Rabbits with Averages of Ranges	Chickens with Averages of Ranges	Eggs with Averages of Ranges
Protein per raw item	445.5 g	140.8 g	6.28 g
Protein source per household/year	107	52	6,370
Kg		7.3	
Protein/year/household	48		40
Percent of			
Protein/year/US	100%	15%	85%
population			
Combined animal	100%		100%

Table 3. Production Statistics for 3 Chickens Per Household

National Average	Small Scale Chicken Operation
Meat protein per household/year	422.4
Egg protein per household/year	1,959-4,898 g
Protein/year/household	2,382-5,321 g
Percent of protein/year/U.S. total need for protein	3.7-7.8%

Table 3 describes the production statistics for eggs from 3 chickens collected over 1 year and the meat from 3 chickens, assuming they were slaughtered at the end of that year. Ranges in values come from the seasonal differences in egg production. During colder months, chickens produce fewer eggs (as low as 2 eggs per week) and during warmer months, chickens can produce up to 5 eggs per week [78, 79]. These values were obtained by using 3 chickens for each of 128.58 million households in America, which is a realistic number of chickens held by representative small hobbyist chicken owners. The ranges come from 2-5 eggs per week being produced by each chicken. The process is shown by equations 9-14. The value of 3 chickens was chosen based on averages compiled from backyard chicken farmers and scaled to account for the difference in access to farming materials and difference in yard size between a typical American home and that of a current backyard chicken farmer.

With equations 9-14, 1,741-3,719 grams of protein can be produced per year for each household if each household in America raises 3 chickens for one year. This value multiplied by 128.58 million households shows that between 223 billion and 478 billion grams of protein demand can be offset by the American population if 3 chickens are raised by each household in America for one year. With this equation and the ranges presented above, the percent of the American population that can have its protein requirements met by raising 3 chickens in every household backyard in America is 3.7-7.8%.

3.5. Economics

Current backyard chicken setups generally range from 3-6 chickens [79-81]. In many backyard setups, however, chickens are raised only for eggs. Most homes in America have enough yard space to sustain a small operation such as this. If every home in America with sufficient space raised 3 egg and meat producing chickens per year, 3.66-7.83% of the protein produced in a year could be offset from the commercial meat industry (and a larger percentage of the commercial chicken egg market).

One of the aspects that makes chicken and egg production differently priced is the manual labor that is paid in an industry setting, but unpaid in a backyard setting. For a small backyard chicken

setup, 1-2 hours of labor are required per day [80]. As a setup grows, more time is required for cleaning, feeding, and maintenance.

The average American family, defined as two or more people living in the same household [82], spends \$678 on meat in a year [83]. Startup costs for a free-range chicken vary from \$200-4,000 depending on local material cost and size of setup [81,84]. Yearly cost for a small chicken setup, assumed here to be 3 chickens, is \$3-7/ bird [79-81].

It also must be considered that all meat and eggs raised in this study are free range and organic if organic feed is used. Most chicken raised in America is factory scale and is therefore raised for significantly less money per bird due to feed costs being in bulk, less space required for each chicken, and bulk cost of maintenance, slaughtering materials, and coop space. One whole industry-produced chicken is generally sold for about \$1.50 per pound in America, but organic chicken sold at stores such as Trader Joe's, Fresh Direct, and Whole Foods can range from \$2.69-\$8.99 per pound [85].

The cost of eggs during non-pandemic times in mainland America averages \$1.54 per dozen [86]. Similar to the higher values seen for organic meat, organic free-range eggs cost \$4.00-7.00/dozen [87]. Further, feed is often sold for as little as 10 cents a pound, meaning that to sustain one chicken for one month, cost of feed is less than one dollar [78]. By another source, a 50-pound bag of chicken feed costs around \$25 depending on location and quality of the feed, and can feed about 6 chickens for a month [80]. This source states that each chicken will need 8.3 pounds of feed per month, but cost for feed is dramatically different with feed for one chicken costing \$4.15 for one month [80]. These differences in feed price will vary greatly depending on location, quality of feed, amount of feed purchased, and amount of feed required for each chicken due to the amount of supplemental food given.

Any other associated costs such as permits, veterinarian bills, slaughtering materials, cost of water and any other seasonally or regionally dependent costs are not taken into account in this model. For the purpose of this study, the following assumptions have been made: the cost of a coop is \$200, \$2 will feed one chicken for a month assuming that chickens are fed supplemental table scraps, insects, and weeds (a rough average according to the two sources quoted above) [78,80], and the initial cost of purchasing each chick is an average of \$5 [80,81]. Based on these assumptions, the total cost of raising 3 chickens for one year comes to \$287 and total cost of raising one chicken is therefore \$96. This value is artificially inflated for long-term systems because the price of building a coop is a one-time cost and if chickens are raised for multiple consecutive years, the average cost will be much lower over time. In second and consecutive years, total cost will be, by the above calculations, about \$29 per chicken per year with no labor cost.

The difference in cost of backyard-raised chicken when compared to store-bought chicken stems from the difference in price of food, price of coops or housing, and price to buy chickens. Industrial chickens are produced in mass quantities and food is bought in bulk which amounts to lower cost per chicken. Some chickens are also set aside as breeder chickens from birth. It can be asserted that backyard raised chickens are of higher value than store bought chicken because they are free-range, organic, and local, thus creating a value-added advantage to distributed production.

These equations and assumed values only work for a small-scale chicken operation. If the number of chickens to be raised exceeds 20 chickens (considered the upper bound for a typical backyard chicken operation) [79-81], a coop must be much larger and building materials will cost more. Assuming the 52 egg producing chickens required to satisfy 100% of one household's protein for one year were produced in a backyard, coop size would more than double from the small-scale operation (under 20 birds) and approximately double in cost (assuming the small-scale coop works for up to 20 chickens, but materials get cheaper per unit when bought in bulk). To gain a rough monetary estimate, cost for the coop will be increased to \$400. The cost to raise 52 backyard chickens is then \$1,604 per year excluding coop cost as a one-time purchase. Per chicken, this value comes to be approximately \$30.85. This is expensive when compared to industry-produced chickens, but it must be considered that this value takes into account not only the meat produced from one chicken, but also one year's worth of eggs (3-5 eggs per week for 35 weeks per year). This yields 105-175 eggs, which is approximately 9-15 dozen eggs. If all of these eggs were purchased at the above stated price

of \$1.54 per dozen, this would offset \$13.86-\$23.10 from the overall cost of one chicken (\$30.85) bringing the cost for the meat of one backyard chicken down to between \$7.75-\$16.99. One whole chicken when purchased from a store costs between \$8.32 and \$11.78 for an average of \$10.05. Industry chickens can be produced at a lower average cost because all aspects of production are performed in bulk, whereas with distributed production, all the externalities from centralized production are by definition ignored and egg production and meat production are separated to gain maximum product and profit for each.

The cost of raising non-pasture-fed rabbits is significantly greater than the previous two scenarios. Non-pasture fed rabbits require a mix of hay, pellets, and fresh vegetables to have a well-rounded diet. Rabbits consume 4-8 ounces of pellets each day [88]. Cost of pellets varies depending on location but is usually around \$15 per 50-pound (22.7 kg) bag [89]. If raised for 12 weeks until slaughter, 21-42 pounds (9.5-19.0 kg) of feed are consumed. This means that the cost of feeding one rabbit for 12 weeks if feed costs \$15 per 50-pound bag is \$6.20-\$12.60. Since rabbits are currently not produced on an industrial scale in America, there is no direct comparison to backyard raised rabbits in the same sense that industrially raised chickens are compared to backyard chickens. However, in the areas where rabbit meat is produced, it is priced out to be \$5-8/pound [73,90]. Dressed rabbits contain 2-4 pounds of usable meat [48]. The average store-bought rabbit will therefore cost between \$10 and \$28. This \$3.80-\$15.40 difference in price between backyard-raised and store-bought rabbit means that much of the cost of store-bought rabbit is labor of raising, transportation, and preservation of meat. In comparing these prices, only price of food was considered since that is the main reoccurring cost. This difference may also stem from commercial markups.

Soybeans can be purchased for \$10.44 per bushel (27.2 kg) in the U.S. [91], which is approximately 38 cents per kg.

4. Discussion

The differences in values for number of rabbits sustained via pasture grazing is due to different values in available data. Method 1 used the Web Soil Survey, which has limited data in certain areas of the country. These shortages of reliable data may lead to artificially low values. Method 2 used a grass growth analysis found in [50]. This study found growth rates of grass to be significantly different across the country and values were averaged for this study. This analysis may create an artificially high number of rabbits per yard. With the differences in values, the actual value of rabbits able to be sustained per yard is to be highly variable across the United States depending on specific soil type, grass type, native vegetation, yard maintenance, precipitation/irrigation and many other factors. It should also be considered that raising rabbits off of solely grass should only be used as an emergency farming method, and that rabbits will produce more and higher quality meat when grass feed is supplemented with pellets and vegetables [88].

The calculations in this study assume that the only source of protein consumed by Americans is meat/soybeans. Many other foods besides meat products such as beans, nuts, and grains contain high levels of protein and are already commonly consumed in combination with beef, pork, and chicken in the average American diet [70]. While the viability of plant-based diets is often contested, ample research shows that plant-based diets can sufficiently meet the protein needs of people during all stages of their life cycle, ranging from childhood to old age [22; 92]. Approximately 1.5% of Americans follow vegetarian diets while 0.5% of Americans follow vegan diets [93], therefore lowering the number of animals required to sustain the population.

When considering the growing demand for meat products worldwide and the potential stress on infrastructures and resources during pandemics, the long-term sustainability of meat production must be assessed. Diets dominated by meat products are the most energy-intensive and environmentally exhaustive [94]. Pimentel & Pimentel [95] show that the average American meat-based diet demands more energy, land, and water resources in comparison to an ovo-lacto vegetarian diet, which raises concern for the sustainability of current meat-based food systems and supports the need for a shift in dietary demands in the face of burgeoning global population and pandemics. While meat is generally thought of as the primary source of protein in developed countries, meat-based

diets are unhealthy [96-98]. Vegetarian diets are associated with lower rates of death from ischemic heart disease, lower cholesterol levels, lower blood pressure, and lower rates of hypertension and type 2 diabetes [21,99].

The financial case for replacing a portion of the mass-produced meat in non-pandemic times is not entirely encouraging. However, in the raising of chickens, much of the cost comes in the form of startup materials. Options are in place in many areas to offset this cost for those who wish to raise chickens on a temporary basis in the form of renting coops and startup materials [81]. However, in times of crisis where a considerable portion of the meat market must significantly raise their prices, backyard raised animals may become much more cost efficient. The meat and poultry index rose by 4.3% nationwide in the month of March, when Coronavirus was officially declared a pandemic by the World Health Organization [100,101].

It must also be considered that the average yard size statistics used for this study may not represent an accurate picture of the number of rabbits to be raised for the entire country. The information represented in this study focuses on individual homes which does not represent the people who live in apartment style or communal housing without yards. The number of people excluded from this study because these living arrangements is estimated to be 17% of the population of the United States which equates to 55.8 million people [102].

For the systems presented in this study to be beneficial, support from local governments needs to be present. Many cities have restrictions on farm animals within city limits because of noise, odor, and spread of disease [103]. In the case of a partial national collapse of the commercial meat industry, a federal override of these municipal laws may be necessary. Certain areas of the country are already becoming more accepting of backyard animals, however, as is the case with San Antonio, Texas where the limit on backyard chickens was raised from three birds to eight in 2017 [79].

Another consideration on the accuracy of data from this study concerning pasture-fed rabbits is the longevity of the grass in American yards over a timespan of multiple years. Traditionally, people mow their lawns and leave grass clippings to decompose and fertilize the soil and promote more grass growth. If all this grass is eaten by pasture-fed rabbits and there is no influx of nutrients into the soil besides composted manure, the future growth of grass in those areas may suffer (some nutrients eaten by people would go into wastewater). This could be counteracted with fertilizer.

Table 4 describes the resources required and outlines some of the basic environmental consequences of raising and producing each type of meat. Data regarding cows is also detailed here to give context to the environmental impact of each animal throughout a typical lifetime until slaughter. Production of beef requires substantially more resources than chicken, rabbit, or soybean production. The effects that the production of large amounts of beef has on the environment are becoming more apparent than ever as the global population grows [104]. Lytle et al. explain that the greenhouse gas emissions per kg of meat associated with cattle production is reduced by more than an order of magnitude when shifting to rabbit production [105].

Table 4. Resources Required to Produce Meat from Different Animals [43,55,106, 108-111].

Animal	Land Area (acres)	Kg CO ₂ Equivalent Output per kg Meat
Cattle	1.5-2	34.6 [43, 108]
Pasture-Fed Rabbit	0.2-1.2	0.0053 [109]
Pellet-Fed Rabbit	0.00069– 0.00092	3.86 [106]
Chicken	0.00032	4.57 [55, 110]

For CO₂, beef produces around 7.57 times the carbon dioxide equivalent that chicken does. One reason for this difference is the fact that cattle only have one offspring at a time, so maintenance during gestation increases energy use. Production of backyard chickens or rabbits has significantly

lower impact because of the lack of transport resources, lack of long-term refrigeration costs, and distributed preparation efforts.

The coronavirus (COVID-19) pandemic has overwhelmed medical and agricultural infrastructures at the regional level. During the coronavirus pandemic, meat packing plants were hotspots for coronavirus transfer and spread. The U.S. consumes 115-125 kg of animal meat (carcass weight) per capita annually [111] and 80% of the meat industry is controlled by four companies [19,20], presenting potentially crucial disruptions in meat supply chains and spurring the need to increase distributed production of meat for food resiliency during pandemics. Overall, to obtain 100% of a household's protein requirements only using the average backyard resources, the only viable solution from the results of this study is the cultivation of soybeans, which could provide between 37 and 74 kg of protein per year. Future work is needed to do a more detailed and granular assessment of backyards in America to see the regions where this would need to be supplemented or provide an excess. If external supplementation is available, the best option is raising chickens while also harvesting eggs. In this case if outside food was provided again chickens could provide all of the average household's protein needs using 52 chickens. Rabbits could also do this with about 107 rabbits using external feed. A smaller fraction (0-50%) of the household's needs could be on average provided by pasture-fed rabbits using only the yard grass. Perhaps the best option is growing soybeans and feeding the residues to rabbits. These values are conservative for all cases. Both rabbits and chickens for example could be fed scraps to increase the yield. Future work is needed to experimentally verify yields for all protein sources investigated here. Data should be gathered studying the potential maximum number of chickens and rabbits in backyards in each state to identify the specific challenges related to high levels of meat production in space-constrained areas.

Household protein production could make sense for other catastrophes. One class of catastrophes would disrupt electricity/industry, and it includes extreme solar storm, high altitude detonation of a nuclear weapon causing an electromagnetic pulse, a super computer virus damaging electricity generating systems [112] or an extreme pandemic causing the desertion of critical industries [113]. In this case, food production would need to be much more local [114]. Soybean production from former lawns would be quite valuable, especially because it fixes nitrogen from the air, which is available for other crops.

Another class of catastrophes would kill crops, including by blocking the sun, caused by supervolcanic eruption, large comet/asteroid, or nuclear war causing the burning of cities and smoke rising into the stratosphere [114]. Though it may be feasible to relocate cold tolerant crops to the tropics, places such as the United States would have difficulty growing crops except indoors [115]. However, most of electricity and industry would still be functioning globally [116]. The existing biomass could form an important source of food. For instance, leaves can be ground up and the liquid that is squeezed out can be boiled to form a leaf protein concentrate [117]. It may be possible to break remaining cellulose into edible sugar at the household scale [118]. Regardless, the residues could be fed to fiber digesting animals including rabbits. Though a cow would typically not fit on a backyard, the biomass from multiple households could be consolidated to a cow. Mushrooms could also be grown in basements and are typically high in protein as a percent of calories. Residues from mushroom growing have already been fed to cattle, sheep, and bison [119], and would probably work for rabbits as well. Another protein option that could be grown at household scale is insects. Particularly valuable would be those insects that could feed on residues from leaf processing and also animal waste [120]. Another option for local food production in sunblocking catastrophes would be methane consuming microbes (single cell protein) because of continuing natural gas supply to houses. Similarly, if electricity is still flowing, it could be used to electrolyze water into oxygen and hydrogen. These could be combined by specialized microbes to create food [121,122]. Combination catastrophes could occur with the sun being blocked and electricity/industry being disabled [123]. In this case, only a subset of the alternative foods would be feasible, including leaf protein concentrate, mushrooms, and rabbits.

5. Conclusions

To safeguard against meat supply shortages, this study analyzed the potential to provide the average American household's entire protein consumption. Overall, to obtain 100% of a household's protein requirements only using the average sized backyard resources, soybean cultivation was found to provide between 37 and 74 kg/year, which is enough for two to four people. If external supplementation of feed is available, raising chickens while also harvesting the concomitant eggs as well as grain fed rabbits can meet 100% of a household's protein requirements. In these cases, 52 chickens and 107 rabbits would be needed, respectively. Using conservative yield estimates, however, only 0-50% of the household's needs could be on average provided by pasture-fed rabbits using only the yard grass as feed. Perhaps the best option is growing soybeans and feeding the residues to rabbits. These values are conservative for all cases and future work is needed to experimentally verify yields for all protein sources investigated here. Data should be gathered studying the potential maximum number of chickens and rabbits in backyards in each state to identify the specific challenges related to high levels of meat production in space-constrained areas.

For the systems presented in this study to be beneficial, support from local, and perhaps federal, government is needed to facilitate distributed meat production in response to a partial national collapse of the commercial meat industry during a pandemic. Resilience to future pandemics and challenges associated with growing meat demands can be incrementally addressed through backyard distributed protein production. Although backyard production of chicken and rabbit meat does not use feed or space as efficiently as current industry processes for these animals, environmental costs due to production, transportation, and refrigeration of meat products would be greatly reduced if more chicken and rabbit meat was consumed and even more so in the case of soybeans. Generally, distributed production of protein was found to be competitive with centralized production of meat if distributed labor costs were ignored. If raising protein by gardening or animal husbandry were not an enjoyable hobby for people, then one should include the opportunity cost of time. This would make backyard protein considerably more expensive; however, in the severe catastrophes where hunger or starvation is the alternative, these food sources could be critical.

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