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How many chickens does it take to make an egg? Animal welfare and environmental benefits of replacing eggs with plant foods at the University of California, and beyond

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Abstract

Our question "How many chickens does it take to make an egg?" was inspired by the successful replacement of egg-based mayonnaise with plant-based mayonnaise in general dining at the University of California, Santa Barbara, in order to increase animal welfare. Our indicator of improved animal welfare due to decreased egg consumption was the reduction in number of chickens in the stressful and unhealthy conditions of the US egg industry. To measure this we calculated the ratio of chickens to eggs and found it takes 6.3 chickens to make 1000 eggs (0.0063 chickens per egg). This equals 158 eggs per chicken, less than half the amount of eggs per laying hen because of mortality from hatching to entering the laying flock, including the disposal of male chicks. In addition, greenhouse gas emissions, irrigation water, reactive nitrogen, and land use would be reduced 43–98% from that of eggs. While the impact of plant-based mayonnaise was relatively small, we also estimated the substitution of eggs with tofu, which had a much greater impact: substituting 50% of eggs with tofu in first-year student breakfasts on all UC campuses would reduce the number of chickens in the egg industry by 9245. If this substitution was made by the US population, the welfare and environmental benefits would be 29 thousand times greater. Reducing egg consumption would greatly improve chicken welfare even if welfare certified eggs are replaced, since the requirements of the most commonly used chicken welfare certification programs do relatively little to reduce chicken suffering.

Keywords Animal welfare · Climate change mitigation · Environmental impact · Food systems · University of California · US egg industry

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Abbreviations

CO_2e	Equivalent carbon dioxide emission; the amount of carbon dioxide emission that would cause the same amount of heating over a given time as the emissions of a mixture of other greenhouse gases
GFI	Global Food Initiative, University of California
GHGEs	Greenhouse gas emissions
MT	Metric ton
NGO	Non governmental organization
SPI	Soy protein isolate
UC	University of California
UCSB	University of California, Santa Barbara
USDA	United States Department of Agriculture

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Introduction

College and university campuses around the world are increasingly aware of their obligation to provide food environments that support student, staff, faculty, and community health, environmental health, climate change mitigation, social justice, and animal welfare. Strategic replacement of animal-source foods with plant foods is a way in which all these goals can be accomplished simultaneously, and many campuses are doing this. In the US for example, offering plant-based foods is one of the strongest trends changing the campus food environment (Middleton and Littler 2019). In the most recent survey of the sustainability efforts of members of the Association for the Advancement of Sustainability in Higher Education, 83% of the 397 higher education institutions reported having a "vegan dining program that makes diverse, complete-protein vegan options available to every member of the campus" (based on data in AASHE 2020). However, campus food environments in the US also reflect the national food environment of which they are a part, which is dominated by unhealthy foods that work against stated campus food system goals (Dhillon et al. 2019; Gonzales et al. 2017; Horacek et al. 2013; Tseng et al. 2016). Many of these unhealthy foods also have relatively greater negative environmental and climate impacts (Swinburn et al. 2019; Willett et al. 2019).

Animal-source foods comprise a large proportion of our food system's environmental, health, social, and animal welfare impacts, and increasing substitution of plant foods for animal-source foods in the diets of populations like that of the US is necessary to respond to the national and global climate, environmental, health, and social justice emergencies (Bajželj et al. 2014; Cleveland 2020; Springmann et al. 2018; Willett et al. 2019). Chickens dominate the poultry industry in the US, accounting for 90% of all animals slaughtered in 2018, 9 billion broilers and 126 million other chickens (which includes egg-type layers, most of which are disposed of in other ways) (based on data in USDA ERS 2019b). In 2016, 87.9 billion eggs were produced in the US, equal to 303 eggs per person, which after adjustments for loss and waste was 184 eggs consumed per person per year in all forms (based on data in USDA ERS 2019a).

Because of the very large number of eggs produced and the dominance of the profit motive, chickens in the US egg industry are exposed to stressful, unhealthy conditions (Singer and Mason 2006; Warren 2018). Eggs also have lower climate (Tilman and Clark 2014) and other environmental impacts than many plant foods (Eshel et al. 2014), and though this has been decreasing due to increasing efficiency (Pelletier et al. 2014), this decrease is associated with reduced chicken welfare. Eating eggs may also have negative health impacts because of the breakfast foods they are normally eaten with in the US; one study found that a decrease in egg consumption was associated with overall increase in nutrient density and health quality (e.g., lower saturated fat, sodium and added sugar, and higher fruit content) (Drewnowski et al. 2018). Eggs themselves may also have negative health impacts due to saturated fat content (Zhong et al. 2019). If reducing egg consumption improved health, it could result in reduced climate impact due to decreased health care costs (Hallström et al. 2017).

The sustainability policy of the University of California (UC) includes a goal for "sustainable food services" of "20% sustainable food products by the year 2020," with "sustainable food" defined as a food or beverage purchase that meets just one of 20 criteria (with the option for adding more) that include those focused on animal welfare, social justice, and environmental sustainability (UCOP 2018, pp. 15, 29–31). The main food policy of the UC, the Global Food Initiative (GFI), has goals that include helping "individuals and communities access safe, affordable and nutritious food while sustaining our natural resources," and finding ways the UC can "leverage its collective buying power and dining practices to create desirable policies and outcomes" (UCOP n.d.). The GFI has supported many programs to improve nutrition and health on campus, including a food and housing security program (UC GFI 2017a), and there are many individual campus projects that aim to reduce animal foods on campus (Cleveland and Jay 2020b). Since 2016 the focus of the GFI has been the Healthy Campus Network (HCN), with the main goal of advancing "a culture of health and well-being" (UC GFI 2017b).

Thus, given the negative impacts of animal-source foods on animal welfare, climate, the environment, and public health, replacing them with plant foods can contribute to many aspects of the UC's food policy goals. This substitution could also contribute to UC's climate change mitigation policy (Cleveland and Jay 2020b). However, food system change is challenging because the for-profit food system still dominates UC and other higher education institution campuses, including soda pouring rights contracts, and fast food franchises (Cleveland and Jay 2020b).

In this paper we report the successful replacement of egg-based mayonnaise with plant-based mayonnaise in the general dining of UC Santa Barbara (UCSB), motivated by concern for animal welfare. Using USDA and other existing data, we estimated the effect of this replacement on the number of chickens in the egg industry and on the environment, including the climate. We extrapolated these results to all dining on the 10 UC campuses. We also estimated the impact of substitution with tofu of 50% of all eggs used to prepare first-year student breakfasts on UC campuses, and 50% of eggs eaten in meals by UC people on and off campus, eaten by UC people and their households, and by all people in the US. We used the number of chickens living in the US egg industry's stressful and unhealthy conditions as the indicator of chicken welfare, because the most widely used welfare certifications for the egg industry are not good measures of welfare.

Chicken welfare in the US egg industry

The main public concern with egg production and consumption, including on college campuses, is the welfare of the chickens needed to produce the huge amount of eggs consumed. A common way of conceptualizing the basis of animal welfare is a middle position between two extremes—animals have no feelings and therefore no right to welfare considerations, and animals are centers of subjective experience including suffering and therefore have the right not to be exploited for human benefit (Sherwin 2010). The middle position states that addressing animal welfare is a matter of balancing costs and benefits to humans with costs and benefits to animals, based on the assumption that humans have a right to eat animals and their products, but that animals' capacity for suffering should be acknowledged and addressed by welfare measures.

While it is difficult to quantify chicken welfare in the egg industry, a number of objective indicators have been identified and are commonly used, including area available per chicken, bone fractures, pecking, debeaking, forced molting, and slaughtering methods. Measurement of these indicators has been used by regulatory agencies to assess the condition of chickens in the egg industry. However, there is a lack of agreement among chicken welfare advocates, researchers, and the egg industry, on how to translate objective measures of these indicators into subjective standards for rating the degree of chicken welfare, and on how these standards should be applied. A number of global (OIE 2018), national (AVMA 2013b) and state bodies (CHSC 2008), NGOs (AHFP 2017a), industry groups (UEP 2017b), and academics (Fernyhough et al. 2020; Schäfer 2019) continue to discuss this issue.

The major challenge is the difficulty of interpreting objective measurements of welfare indicators in terms of chickens' subjective states, which is required by the very concept of "animal welfare." It is important to note that the assumption that chickens and other domestic animals have the capacity to suffer is recognized in all welfare standards. For example, chapter 13.8 of California's Health and Safety Code is titled "Farm Animal Cruelty" (CHSC 2008), and the American Veterinary Medical Association sees its obligation to provide guidance for relieving "unnecessary pain and suffering" (AVMA 2013a, p. 5).

Conventional egg production and chicken welfare

The modernization and industrialization of chicken egg and meat production began in the US at the beginning of the twentieth century, with a focus on breeding for tolerance of intense confinement (Warren 2018, pp. 110–111), and has been accompanied by a decrease in chicken welfare (Sherwin 2010). This process has been motivated by the drive for increased profits through increasing production efficiency by means of higher animal densities, larger number of animals per production unit, environmental changes including in feed and housing, and the breeding and management of chickens for these conditions (Fernyhough et al. 2020; Kidd and Anderson 2019).

The system of keeping small flocks of laying hens on the ground began to be replaced in the US in the 1930s with cages housing one chicken, and "swept the country in the 1950′s" due to increased profits (Kidd and Anderson 2019, 776). In conventional settings in the US today, battery cages of six to ten hens per cage in multi-tiered cages are common, with automated feeding, watering, and egg and manure collection (Greene and Cowan 2014, p. 7), and space per hen much smaller than required for good welfare. These changes were accompanied by the use of hen body heat for winter heating of layer houses, which reduced costs but meant "minimal ventilation for air circulation and ammonia control" (Kidd and Anderson 2019, pp. 778–779).

The English veterinary scientist Chris Sherwin, who did extensive research on animal behavior, summarized the effects of this housing on laying hens in terms of welfare and ethics. While hens require 1150–1876 cm^2 (178–291 $in.^2$) for some basic natural behaviors (preening, turning, wing flapping), space in cage systems is well below this, and in cage-free and free range conditions space in structures is also highly limited, and many chickens may not leave these crowded structures to go outside (Sherwin 2010). These conditions can cause bone weakness due to physical restriction, which result in a higher rate of fractures. Keel bone fractures are common, are correlated with behavior indicating pain, and one study found that hens with severe keel bone fractures compared with control had brain neuron indications of chronic pain and depression (Armstrong et al. 2020). Breeding for smaller size and a higher egg production also increases efficiency and profits, but could deplete the chicken's calcium reserves and increase bone fragility (Fernyhough et al. 2020). Bone fragility is likely an important cause for keel bone fractures in laying hens that may result from internal pressure of egg laying (Thøfner et al. 2020).

Pecking other hens has been deemed the most important welfare issue for laying hens due to its high prevalence and the injuries it causes, and because it sometimes leads to cannibalism (Sherwin 2010, p. 245). Pecking in cage systems is likely caused by stressful conditions due to lack of space and alternative pecking targets, and to the large flock sizes in alternatives systems, including free range. To prevent this, beaks of female chicks are often trimmed, i.e. partially amputated, without anesthesia, yet pecking and cannibalism still occur after debeaking. In addition to the acute pain of the debeaking process, other behaviors post-debeaking suggest it causes chronic pain. When some of the fibers that were originally removed from debeaking grow back, they form masses of intertwining nerve fibers, that exhibit similar discharge patterns as human amputees with chronic phantom limb pain (Duncan et al. 1989; Sherwin 2010, p. 246). Hens may also have parts of their toes amputated to reduce clawing at each other (Fraser et al. 2001).

Forced molting of hens has been a common practice to extend the period of economically profitable egg laying, which involves food restriction, and until recently food removal, until hens lose 30% of their weight (Bell 2003). Other methods of forced molting include low nutrient rations, feed additives, and lighting alterations. At the end of their productive lives hens are gathered, shipped and slaughtered, often resulting in emotional stress and physical injuries (Sherwin 2010).

Due to differing selection criteria in breeding for broiler-type and table egg-type chickens, a "highly negative correlation exists between fattening and laying performance," so that male egg-type chicks cannot be economically raised for meat (Krautwald-Junghanns et al. 2017). Therefore, all male table egg-type chicks (about 50%), are killed soon after hatching. In the US this is most often done by maceration with an "apparatus having rotating blades or projections [which] causes immediate fragmentation and death" and is an officially approved method (AVMA 2013a, p. 41). United Egg Producers, which represents the interests of 95% of US egg producers, has stated a goal of eliminating male chick culling by 2020 (UEP 2016), and there is research on methods for doing so at scale (Vogel 2019).

Chicken sentience and the origin of animal welfare concerns

In the West, concerns about sentience, the capacity to feel pain and pleasure, and the cognitive capacities of animals can be found in antiquity (Stuart 2008), with increasing attention around the early twentieth century as essayists (Salt 1894) and investigative journalists (Sinclair 1906) began to write about the treatment of animals and the conditions in which they were kept in the industrializing world. Toward the end of the twentieth century, philosophers and other academics began to argue in detail about the moral status of animals (Regan 1983; Singer 1975), with some advocating complete abolition of animals for human use (Francione 1996).

Primarily focusing on sentience, Singer (1975) reviewed the then rapidly growing agribusiness sector's focus on economies of scale for chickens and eggs, which were previously less commonly consumed in the United States. Singer discussed increasing confinement of chickens in large numbers, the disruption of natural environmental conditions in order to facilitate rapid growth and egg laying, and other practices mentioned above, such as debeaking chickens due to aggression in crowded conditions. The philosophical argumentation and vivid descriptions of the conditions of animals made Singer's work arguably the lead catalyst for the animal rights movement (Villanueva 2016).

Evidence for chicken sentience includes behaviors and physiological responses associated with negative emotional states such as fear, frustration, and possibly even depression and boredom (Sherwin 2010, 242). Attribution of these more nuanced emotions increases in people after they engage in interactive training with chickens (Hazel et al. 2015). There is also strong evidence that chickens have cognitive abilities including for stage 4 object permanence in social circumstances (comprehension of object location when concealment is observed), simple numerical ordinality, episodic memory, self-control for increased reward, logical inference of social status, emotional response from anticipation, and many others (Marino 2017).

Status of chicken welfare regulations and voluntary certifications

Although increasing industrialization of animal production for food resulted in animal welfare regulations for slaughter in 1958 in the US (which have continued to be amended), poultry have been excluded from the act (USC 2014, 7 U.S.C. § 1901–1907 (1958)). There are currently no US federal regulations for chicken welfare in the table egg industry. USDA regulations for organically produced eggs began to include spacing requirements and restrictions on total confinement of chickens (including egg layers) in 2016, but were overturned in 2018 (Goodkind 2018).

Some state-level regulations on egg-type layers do exist. For example, California has passed two ballot propositions, Proposition 2 in 2008 (Ballotpedia 2015), which was superseded by Proposition 12 in 2018 (Ballotpedia 2018), that include some regulations on egg operations regarding confinement "in a cruel manner" (CHSC 2008). Proposition 12 requires that egg-type layers must be provided a minimum of 144 square inches of space each by 2020, and must be kept in a cage-free environment by 2022 with the same stipulated minimum space per hen (Ballotpedia 2018). This regulation applies not just to eggs produced in the state, but to any producer that sells eggs in the state.

California Proposition 12 was supported by most animal welfare advocates, but others saw it as too weak, and thereby misleading to consumers (McGreevy 2018). For example, PETA (People for the Ethical Treatment of Animals) stated that Proposition 12 allows the equivalent industry standards for conventional hens such as the restricted space per bird and sourcing chicks from hatcheries that practice debeaking and maceration of males chicks (Toliver 2019). Cage-free conditions could result in increased debeaking due to additional social stress from large flock size, high population concentrations due to inadequate space in enclosures, and poor pasture conditions and other factors that mean most hens will not venture outside.

Many groups also sponsor voluntary chicken welfare certification standards for eggs. Producers who are certified can use the certification label, although most of these are potentially misleading to consumers (Strom 2017). For example the certification standards of the main industry group, United Egg Producers, for space in cage systems are "in the range of 67 to 86 square inches of usable space per bird to optimize hen welfare" (UEP 2017a, 19), and for cage-free systems 1.0 to 1.5 ft^2 per bird, depending on the breed and the structure (UEP 2017b, 20). They also have an employee code of conduct stating that birds must be "handled with respect and dignity," and employees must agree to "minimize stress" (UEP 2017b), however, it is not clear how well these codes are enforced. The voluntary standards for chicken welfare in the table egg industry have a history of deception and lack of enforcement (Singer and Mason 2006, pp. 37–41).

American Humane Farm Program (AHFP), launched in 2000, is the first farm animal welfare audit program to set up standards for different levels of welfare, and is the largest independent certifying organization, with the lowest standards according to a number of critics (Strom 2017). AHFP have published detailed guidelines for free-range and pasture (AHFP 2017b), and cage-free (AHFP 2017a) certifications. However, the cage-free requirement is the same as United Egg Producers', 1.0 to 1.5 ft^2 per bird (AHFP 2017a, p. 20). AHFP standards still allow debeaking, and only require compliance with 85% of the standards for certification.

American Welfare Approved (AWA) have the strictest standards of all other third party certifications, including a flock size limit of 500 and large space requirement for hens, 1.8 ft^2 indoors and 4 ft^2 outdoors, prohibition of forced molting and debeaking or other mutilation (AWA 2018, pp. 8, 18–19). However, because certification labels may appear to be the same to consumers, most companies using welfare certification opt for more lenient ones (Strom 2017). For example, according to the AWA website, in 2020 only 10 small egg producers in the US were AWA certified.

At the global level, the World Organisation for Animal Health is the body that issues animal welfare standards, and currently has 182 member nations, including the US. It is primarily concerned with animal health, but is also the "leading international organization for animal welfare," which is closely linked to health. Its current draft chapter on laying hen welfare includes a detailed list of the indicators of hen welfare, but recognizes that these will not usually be implemented because of their cost (OIE 2018).

The inadequacy of industry and voluntary certification and regulation suggests that independent government regulation is needed to ensure humane conditions in egg production (Parker et al. 2018). The middle ground approach to welfare discussed above is severely limited in how much it can improve chicken welfare given the large and growing demand for eggs and the profit motives of producers (Fernyhough et al. 2020; Sherwin 2010). While per capita egg consumption in the US based on loss-adjusted availability has decreased 11.5% from 197 the 1970s to 174 in the most recent 10 years (2008–2017), the population of the US has grown 60%, so that the total eggs consumed increased from 43 billion in 1970 to 61 billion in 2017 (based on data in USDA ERS 2019a).

While sentience as the capacity to suffer is the primary driver of Singer's ethical argument for strong animal welfare considerations, the increasing scientific evidence for chicken sentience as consciousness, and for their cognitive abilities, supports stronger ethical positions. For instance, Regan (1983) argues that animals have the right to not be used for human purposes based on his position an animal is an "experiencing subject of a life" that matters to itself. Because of the increasing scientific evidence for chickens' subjective experience or self awareness (e.g. Garnham and Løvlie 2018; Marino 2017; Nicol 2015) and its potential to bolster positions similar to Regan's, the sense of responsibility for seeking alternatives to consuming chickens and their eggs may increase. However, government regulation and voluntary welfare standards remain incongruent with the ethical concerns based on scientific data. Therefore, the most effective way for consumers to support increased chicken welfare in the egg industry is arguably to reduce or eliminate eggs from their diets (Sherwin 2010, p. 254; Singer and Mason 2006, p. 110), which reduces the number of chickens in the poor welfare conditions of the US egg industry, and is the measure of welfare we use in this paper.

Methods

Our research methods comprised three main areas. First, we collected data on mayonnaise use for our case study of substituting plant-based for egg-based mayonnaise in general dining at UCSB. We also created counterfactual scenarios for this substitution on all UC campuses, and for estimating the impact of substitution with tofu of 50% of eggs for different populations. Second, we reviewed the literature on chicken welfare in the US egg industry in order to evaluate indicators and goals of chicken welfare, and analyzed USDA data to estimate chicken lives per egg including change over time. In the last step we calculated the effect of reduced egg consumption for our scenarios as the reduction in the number of chickens in the egg industry (chicken lives per egg) and in environmental impact.

Case study and scenarios

Our case study was the substitution of plant-based for egg-based mayonnaise in UCSB's general dining, for which we used purchase data to calculate the amount of mayonnaise used. We also created counterfactual scenarios for the substitution of plant-based for egg-based mayonnaise in residential dining on one UC campus based on reported mayonnaise purchases, and extrapolated this result to all 10 UC campuses based on our estimate of the number of meals eaten on campus (Table S4).

We also estimated the effect on chicken welfare and the environment of substituting tofu for 50% of the eggs consumed, based on the average number of eggs produced annually (see Table 1 below), adjusted for loss and waste from farm gate to the institutional level (1.5%) based on USDA loss-adjusted food availability (LAFA) data (USDA ERS 2019a). Total eggs consumed includes eggs in shell as well as "processed" or "broken eggs," which comprise about one-third of the eggs consumed in the US, including as liquid, dried, or frozen eggs, for example as ingredients in food products. We made this substitution for 50% of eggs used to prepare first-year student breakfasts on the 10 UC campuses, assuming eggs were only eaten at one meal per day (breakfast), and comprised only one-third of total eggs consumed, which likely underestimates egg consumption. We also made this substitution for 50% of eggs eaten in meals by UC people on and off campus, eaten by UC people and their households, and by all people in the US. To find the number of eggs that would need to be produced (equal to number at the "primary" or farm gate level) to supply the number at the institutional (i.e., university dining) level, we adjusted the number of eggs used in university dining for loss through the retail/institutional level using USDA data on loss adjusted egg availability (USDA ERS 2018).

To estimate the amount of mayonnaise and eggs eaten, we made assumptions about meals eaten on campus by the different components of the campus population. We assumed that first-year students lived in residence halls and ate all three meals per day on campus seven days per week, 243 days per academic year. We assumed that all other students ate one meal a day (lunch) on campus five days per week, 174 days per academic year. We assumed staff and faculty ate one meal per day on campus (lunch), five days per week, 48 weeks per year. These numbers don't include snacks, or other meals eaten by summer session students, summer program participants, or attendees at academic conferences, sport, entertainment or other special events, or visitors. For spillover to off-campus meals of the campus population we assumed three meals per day for the total UC population. For spillover to households of campus population we assumed the household size including the UC person was equal to the mean for California 2013–2017: 2.96 persons (USCB 2020).

Chicken lives

We used the number of chicken lives in the US egg industry as the measure of chicken welfare for our case study and counterfactual scenarios, since as described above, most welfare certifications and any changes made to receive certification result in marginal improvements in welfare. The UCSB general dining case study was previously using mayonnaise with eggs that had the American Humane Certified cage-free certification, which lacks objective evidence for substantially reducing animal suffering compared with conventional production. We did not consider possible effects of reduced egg production on the welfare of the remaining chickens.

We used USDA data to estimate the total chicken lives per egg, including: chickens and eggs for January 2018 (USDA NASS 2018a) and the annual summary for 2017 (USDA NASS 2018b), hatchery production (USDA NASS 2018c), and egg production cycles (USDA NASS 2005). We estimated the number of chicken lives required to produce one egg by dividing the mean of number of all table egg-type chicks (both male and female) hatched from eggs of hens in the multiplier flock, by the mean number of table eggs produced, using USDA data for the 12 months December 2016–November 2017.

The null hypothesis that the median for the month-to-month changes in population size for this 12-month sample equal zero, could not be rejected based on the one-sample Wilcoxon Signed Rank test ($P = 0.5693$) (SAS Institute Inc. 2013). Therefore we assumed that the total egg-type layer flock was stable for this period. In a stable population the number of hens added from the pullet (immature hen) flock each month to the table egg laying flock (for which data are not available) would equal the number removed each month, which is reported by the USDA. We calculated the mean number of months laying hens live after entering the laying flock, i.e. how many months it takes to completely replace the laying flock, by dividing mean number of hens from the pullet flock added each month to the table egg laying flock into the mean number in the laying flock for a period of 12 months. We calculated the mortality rate from hatching to entry of pullets into the laying flock as: 1 − (mean number of hens from the pullet flock added each month/mean number of egg-type chicks hatched each month).

Table 1 Estimation of eggs per chicken[a] in the US egg production industry

	1. Table egg-type chicks hatched[c]	Layers[b] removed from flock during the month				Layers[b] on hand during the month				10. Table egg production[d]
		2. Layers sold for slaughter[d]	3. Layers eliminated, other[d]	4. Total layers removed from flock: columns (2+3)	5. Table egg-type layers[c] removed from flock: columns {4*[(6+8)/(6+7)]}	6. Table egg-type table egg layers[d]	7. All hatching layers (broiler egg-type+table egg-type)[d]	8.Table egg-type hatching egg layers[d]	9. Total table egg-type layers[e]: columns (6+8)	
2016 December	45,731,000	14,359,000	10,307,000	24,666,000	21,075,102	318,956,000	58,415,000	3,477,000	322,433,000	7,953,900,000
2017 January	45,367,000	15,899,000	9,494,000	25,393,000	21,671,142	318,495,000	58,703,000	3,417,000	321,912,000	7,916,400,000
February	48,127,000	15,099,000	9,010,000	24,109,000	20,539,489	317,258,000	59,083,000	3,363,000	320,621,000	7,095,800,000
March	55,919,000	16,192,000	10,530,000	26,722,000	22,728,156	316,664,000	59,593,000	3,358,000	320,022,000	7,861,500,000
April	52,762,000	13,524,000	13,479,000	27,003,000	22,928,274	315,770,000	59,978,000	3,278,000	319,048,000	7,572,800,000
May	53,506,000	16,679,000	9,347,000	26,026,000	22,054,625	313,464,000	60,178,000	3,163,000	316,627,000	7,764,500,000
June	49,722,000	14,347,000	9,481,000	23,828,000	20,172,066	312,162,000	60,268,000	3,126,000	315,288,000	7,513,800,000
July	41,862,000	14,930,000	9,096,000	24,026,000	20,348,326	312,412,000	60,220,000	3,181,000	315,593,000	7,782,100,000
August	45,861,000	15,121,000	8,783,000	23,904,000	20,269,310	313,841,000	60,060,000	3,207,000	317,048,000	7,755,200,000
September	42,725,000	13,038,000	8,637,000	21,675,000	18,383,671	315,502,000	60,246,000	3,189,000	318,691,000	7,456,600,000
October	51,495,000	14,586,000	8,796,000	23,382,000	19,849,167	317,758,000	60,270,000	3,153,000	320,911,000	7,763,300,000
November	48,344,000	12,893,000	7,516,000	20,409,000	17,363,299	320,748,000	60,072,000	3,241,000	323,989,000	7,676,300,000
Mean	48,451,750	14,722,250	9,539,667	24,261,917	20,615,014	316,085,833	59,757,167	3,262,750	319,348,583	7,676,016,667
SD	4,190,526	1,141,193	1,403,673	1,844,518	1,574,477	2,606,555	631,661	110,095	2,676,239	228,060,989
Total annual	581,421,000	176,667,000	114,476,000	291,143,000	247,380,168					92,112,200,000

[a]Chicken = both male and female of any age

[b]Layer = mature female chicken producing marketable eggs, usually at least 20 weeks old (USDA NASS 2005, p. 9). "Layers" in columns 2–4 refer to all three types of layers: broiler-type hatchery supply layers, table egg-type hatchery supply layers, and table egg-type layers

[c]Data from (USDA NASS 2018c). Unless otherwise specified "table egg-type" refers to all table egg-type chickens, both those designated to produce table eggs and those designated to produce hatching eggs

[d]Data from (USDA NASS 2018b)

[e]Table egg-type layers in this table refers to both table egg-type table egg layers and table egg-type hatching egg layers

Additional calculations:

0.0063: Chicken lives (table egg)$^{-1}$ = (mean table egg-type chicks hatched)/(mean eggs produced), = (column 1 ave.)/(column 10 mean)

24.04: Table eggs (table egg-type layer)$^{-1}$ mo^{-1} = (column 10 mean mo^{-1})/(column 9 mean)

372.35: Table eggs (table egg-type layer)$^{-1}$ over life as layer = (mean table eggs (table egg-type layer)$^{-1}$ mo^{-1}) * (life expectancy as table egg-type layer in months)

2.35: Chickens (table egg-type layer)$^{-1}$ = (column 1)/(column 5) = (egg-type layers hatched mo^{-1}) / (mean table egg-type layers added to flock mo^{-1}) = [mean life expectancy as table egg-type layer (months)]/[mean life expectancy table egg-type layers at hatching (months)]

158.43: Table eggs chicken^{-1} over life = [table eggs (table egg-type layer)$^{-1}$ over life]/[chickens (table egg-type layer^{-1})], = [(column 10)/(column 1)], = (mean life expectancy at hatching, months) * [Table eggs (table egg-type layer)$^{-1}$ mo^{-1}]

0.0063: Chicken lives egg^{-1} = [1/(Table eggs chicken)$^{-1}$ over life]

6.59: Mean time table egg-type chickens live (months), from hatching = (column 9 mean.)/(column 1 mean. mo^{-1})

15.49: Number of months before all birds in the flock are completely replaced, = (column 9 ave.)/(column 5 mean mo^{-1}). Assumes population size is stable, so that table egg-type layers removed = table egg-type layers added

0.57: Mean mortality rate of table egg-type chickens, from hatching to entering table egg-type layer flock

We also assembled USDA data on chicken lives per egg beginning with the 1960s (the earliest data available) through 2018, and tested the null hypothesis that there was no change over time using the Kruskal–Wallis analysis (SAS Institute Inc. 2013), followed by the Dunn's test of pair-wise significant differences to discriminate between decades (Elliott and Hynan 2011).

Welfare and environmental impacts

To estimate the change in welfare and environmental impacts of reduced egg consumption in each of our scenarios, we assumed reduced consumption would have a direct effect on production with no rebound, i.e., no compensating increase in consumption and production elsewhere.

We estimated the environmental impacts (greenhouse gas emissions [GHGE], blue [irrigation] water, reactive nitrogen, and land use) using one egg as the functional unit. The system boundaries for our calculations were from table egg-type hatching eggs to farm gate, with egg loss and waste extended to post-consumer (plate waste) stage. We did not include breeding or multiplier flocks (Fig. 1, below).

We used environmental impact intensities for the US egg industry for 2010 (Pelletier et al. 2014), which did not include the environmental impact of eggs beyond the farm gate, including from processing, packaging, transport, or disposing of post-consumer food waste (e.g., in landfills), making our estimates conservative. We assessed the environmental impact of plant food substituted for egg in mayonnaise as approximately that of soy protein isolate (SPI, 14% of mass), soybean oil (21% of mass), and water (64% of mass), which combined contain the common nutrients and mass contents of eggs. Egg yolks appear to be a common ingredient in mayonnaise in addition to whole eggs, so we increased the fat content of the egg replacement compared to whole eggs. Since recipes for commercial foods are not available, we used the value for egg content of 6.7% mass-based found in an analysis by Eat JUST, Inc. of competitors' egg-based mayonnaise products, using data on ingredients and nutritional content (Sheldon et al. 2017, p. 29).

GHGE for SPI was taken from Braun et al. (2016), and for soybean oil from Poore and Nemecek (2018). Water footprint for the mayonnaise substitute was estimated by using water footprints for processing SPI (Berardy et al. 2015) and

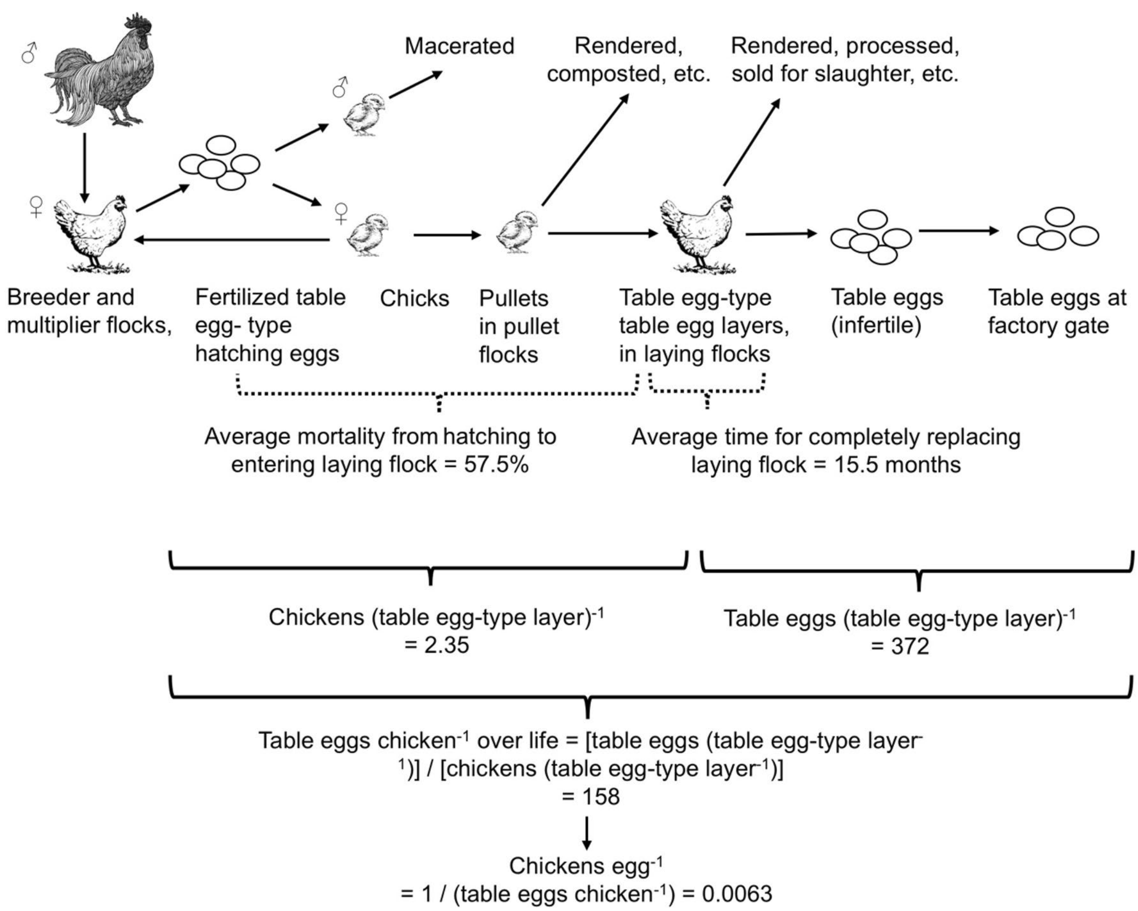

Fig. 1 Life cycle of table egg-type chickens, and chicken lives per egg, in the U.S. egg production industry. See Table 1

general water footprint for growing soybeans (Eshel et al. 2014), with a three-to-one mass ratio for conversion from dry soybean to SPI. Because the SPI calculation resulted in the entire water footprint for soybean production attributed to SPI, to prevent double-counting, we did not add additional water footprint from soybean oil. This estimate is conservative, as more byproducts than oil and SPI result from processing (e.g., leftover meal containing carbohydrates). Reactive nitrogen and land use for soybean were calculated from agricultural data in Eshel et al. (2014), again with a conservatively large attribution to SPI with carryover assumed to also apply to soybean oil.

For estimating the environmental effect of replacing 50% of all egg consumption with plant-based alternatives, we used life cycle assessment data for tofu manufactured in California and substituted tofu for the eggs on a mass basis (Mejia et al. 2018). For water, reactive nitrogen, and land use, we used data from Eshel et al. (2014) for dry soybeans, and the value of 138 g of dry soybean per 350 g tofu from Mejia et al. (2018). Our land use calculation for tofu used data on soy from Eshel et al. because it was slightly larger than Mejia et al.'s direct calculation for tofu, making our estimate more conservative. More information on our methods for estimating environmental impact of substituting plant food for eggs is in the supplementary information (section S1).

Results and discussion

Institutional food change

The production manager of UCSB general dining (MB) became aware of the inhumane and environmentally destructive nature of the animal-source food industry before beginning this job. His goal for the food system was an 80% plant-based diet: "I care about animal welfare and our planet and I think that we could all live with more fruit and vegetables in our diets and less meat." In his first position at UCSB his main responsibility was preparing soups, and the first big change he made was to offer a vegan as well as a non-vegan soup. The vegan soup was very successful, and in response to student requests for more vegan options, he was able to add a number of new vegan salads, wraps, snacks, and sandwiches. Some examples are grilled veggie sandwich, quinoa wrap, brown rice salad, orzo salad, spinach salad, and Thai noodle salad.

When approached by an undergraduate student (AH) who had become interested in increasing the animal welfare status of foods on campus, the dining production manager was therefore receptive. The student began researching the potential for changing to animal-source foods with higher animal welfare ratings by searching the dining data base for animal products used and looking for alternatives. The first criterion for choosing an alternative was a minimal impact on price, yet animal products with higher welfare ratings were also significantly more expensive, and the welfare certifications were of questionable value, as discussed above.

This led AH to search for alternative plant-based options, and to test the effect of reducing portion size in sample menu items in order to offset prices when they were higher. She decided to focus on replacement of egg-based with plant-based mayonnaise since there were a number of plant-based products available and mayonnaise is a minor portion of recipes, although this meant it would have a relatively small impact. In addition, general dining on campus at the time was using mayonnaise with the American Humane Certified cage-free certification for the eggs in the ingredients, which lacks evidence for effectiveness in improving welfare.

The second criterion was culinary quality. Plant-based mayonnaise options were tested for consistency, use in recipes, and taste. Chefs, managers, and purchasing personnel conducted blind taste tests of the different plant-based mayonnaises available through the distributor and the currently used mayonnaise. They found that the plant-based options became watery when lemon juice, herbs, and other ingredients were added in food preparation, did not have the same taste as egg-based mayonnaise, and were more expensive. Therefore, the plant-based mayonnaise from Eat JUST, Inc (formerly Hampton Creek) was also tested, even though it was not available from the distributor. Its processing and taste qualities were found to be comparable to the currently used egg-based mayonnaise, it could be directly substituted in recipes, and its cost was also slightly less.

The third criterion for selecting a plant-based mayonnaise was logistics, including dock time, and the amount the supplier could deliver in relation to both quantity required and the available storage space. Eat JUST, Inc. also met this criterion, so the current distributor was asked to pursue a contract with the company, which took only a few weeks, and plant-based mayonnaise replaced all egg-based mayonnaise in general dining by December 2016.

Chicken lives per egg in the US egg production industry

Table egg-type chicken populations in the US egg industry comprise primary breeder flocks of elite (pedigree/foundation) birds, great-grandparent and grandparent birds, and multiplier flocks that lay fertile eggs which produce both male and female chicks (Fig. 1) (USDA APHIS 2011; USDA NASS 2005). Of these chicks, the males are disposed of, 1% of females are placed in multiplier flocks that will produce more fertilized hatching eggs, and all other females are placed into pullet flocks that transition into layer flocks to produce table eggs. The life cycle ends with the death of the table egg-type layer. The mortality rate of table egg-type chickens (including males, layers producing table eggs, and layers producing hatching eggs) from hatching to entering the laying flock is 57% (Table 1), mostly the result of culling male chicks which are usually macerated mechanically, but also from mortality of female chicks and pullets.

From entry into the table egg-type layer flock (both hatching egg and table egg layers) until removal from the flock the mean time is 15.5 months (Table 1) before being removed and "sold for slaughter" or "rendered, died, destroyed, composted, or disappeared for any reason (other than sold)" (USDA NASS 2018b, p. 16). Whole flocks are often eliminated ("depopulated") when their production rate becomes unprofitable. The most common methods used by table egg production units to "dispose of spent hens" are "rendering" (47%) and "processing" (39%) (USDA APHIS 2011, p. 30).

From the time chicks hatch from eggs laid by multiplier flock hens through the end of the laying hen's life, we found the number of chickens per egg was 0.0063 (6.3 chickens per 1000 eggs). As a result, eggs per table egg-type chicken per year (158) are only 42.5% of the mean number of table eggs produced per table egg-type layer (372, or 0.0027 laying hens per egg) (Fig. 1, Table 1). Including male chicks and female mortality before entering the laying flock in the analysis of the life cycle of egg-type chickens shows that the number of chickens it takes to make an egg is more than twice what is commonly assumed when only adult hens in the laying flocks are included, with a corresponding increase in lives saved when egg consumption is reduced.

Based on USDA data, chicken lives per egg appear to have generally decreased since 1960 (Fig. 2), with a 21% reduction in the mean from 1960–79 (0.0078) to 1980–2018 (0.0061). A test of the null hypothesis that there was no change in means over time using Kruskal–Wallis analysis was rejected, so we used Dunn's test of pair-wise differences to see which decades differed significantly (Elliott and Hynan 2011). The 1960s and the 1970s mean chicken lives per egg were not different from each other, nor were the means of each of the four decades 1980s–2010s, and show a reduction from the 1960s–1970s to 1980s–2010s. However, the means for the 1970s and the 2010s were also not different from each other, likely due to the largest and most expensive avian flu outbreak in the US to date in 2015 that mainly affected laying hens and turkeys (Hicks et al. 2020). Beginning in March 2015, with a large increase in cases of H5N2 avian flu avian influenza in the Midwest, and the end of the outbreak in June 2015, over 50.4 million birds were culled or died, costing the industry hundreds of million of dollars (Hicks et al. 2020). Chicken lives per egg increased between 2014 and 2015, and remained relatively high through 2018.

The reduction in chicken lives per egg from the 1960s–1970s to the 1980s–2000s (Fig. 2) was accompanied

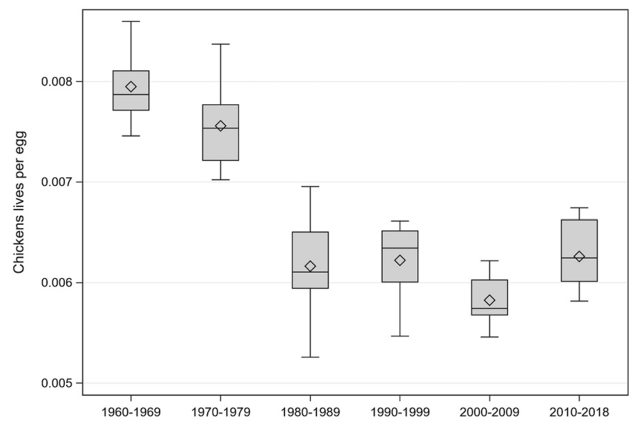

Fig. 2 Box-and-whisker plot of chicken lives per egg in the US egg industry, 1960–2018. Boxes denote first and third quartiles, horizontal line within the box is the median value, diamond is the mean, and whiskers denote maximum and minimum values. Data sources: 1960–1989: (Weimar and Cromer 1990), 1990–92: (Madison and Perez 1994), 1993–2018: (USDA ESMIS 2020a, b)

by consolidation of the US egg industry, beginning in the 1960s and 1970s, and other changes to increase efficiency and profitability (see "Chicken welfare" section). The number of chickens it takes to make an egg is an important indicator of egg production efficiency and profit. For example, chicken lives per egg decreased 27% from 0.0079 in 1960–69 to 0.0058 in 2000–2009 (Fig. 2), while from 1960 to 2010 pullet mortality rate decreased 70% and hen mortality rate decreased 57%, while the number of pullets sourced per metric ton of eggs decreased 22%, and daily egg production per hen increased 27% (Pelletier et al. 2014, p. 246). Decreasing mortality is an important way to increase production efficiency and has been assumed to increase welfare, although it is associated with cage systems and beak trimming (Weeks et al. 2016). In addition to decreased mortality, many other changes to increase efficiency and profits, including increasing density of housing, minimal ventilation to reduce heating costs, breeding for smaller size and to extend laying cycles, are associated with decreasing chicken lives per egg, but increasing stress, injury and suffering (discussed above in section "Chicken welfare in the US egg industry") (Fernyhough et al. 2020).

We used chicken lives per egg as the basis for estimating the reduction in the number of chickens in the egg industry and in environmental impact, when eggs in the food supply are reduced.

Impact of reduced egg consumption on chicken welfare and the environment

We found that the impact on chicken welfare of replacing egg-based mayonnaise with plant-based mayonnaise in the

UCSB general dining case study was reduction in the number of chickens in the egg industry by 14 per year (Fig. 3, Table 2). The annual environmental impact would also be reduced: greenhouse gas emissions by 0.11 MT of CO_2e, irrigation water consumption by 14 m^3, reactive nitrogen (Nr) by 4.0 kg, and land use by 0.03 ha. If the local campus residential dining service also made the change, 76 additional chicken lives would be saved, and if all UC campuses residential and general dining services did this 924 lives would be saved; environmental impacts would be reduced proportionately (Table 2).

We also created scenarios for substituting 50% of eggs consumed in the diet with a plant-based food, tofu (Fig. 4, Table 2). For the campus scenario we conservatively assumed that all eggs were eaten at breakfast, and only by first-year students, and implemented on all UC campuses. This would result in the reduction of chickens in the egg industry by 9,245, and in greenhouse gas emissions by 85 MT of CO_2e, irrigation water consumption by 8213 m^3, reactive nitrogen (Nr) by 2627 kg, and land use by 22 ha (Table 1, Fig. 4). If there was spillover from this change on campus to substituting 50% of eggs eaten at all meals by UC people on and off campus with tofu the effects on chicken welfare and environmental impacts would be 43 times greater, and if the households of all university people also made this change the effects would be127 times greater (Table 2). If there was spillover of this change to the entire US population, egg production would be reduced by 46 billion eggs per year, and the increased welfare and environmental impact would be 29,000 times that of the UC on-campus scenario (Table 2).

The change to plant-based from egg-based mayonnaise reduced GHGE 43%, blue water 77%, reactive nitrogen 98%, and land used 63% (Table 2, Table 3). In comparison, Eat JUST, Inc.'s life cycle analysis found that their plant-based mayonnaise products had 42% (± 12%) lower GHGE and 93% (± 20%) lower ground and surface water consumption and than "corresponding market share-weighted" competing egg-based products (Sheldon et al. 2017, pp. 25–26). The replacement of all eggs by tofu reduced impacts for the four environmental variables by 53–98% (Table 2, Table 3). There are also commercial plant-based egg substitutes increasingly available, but their higher level of processing, packaging and advertising would make their environmental impacts greater than tofu, and greater still than less processed substitutes like beans or lentils.

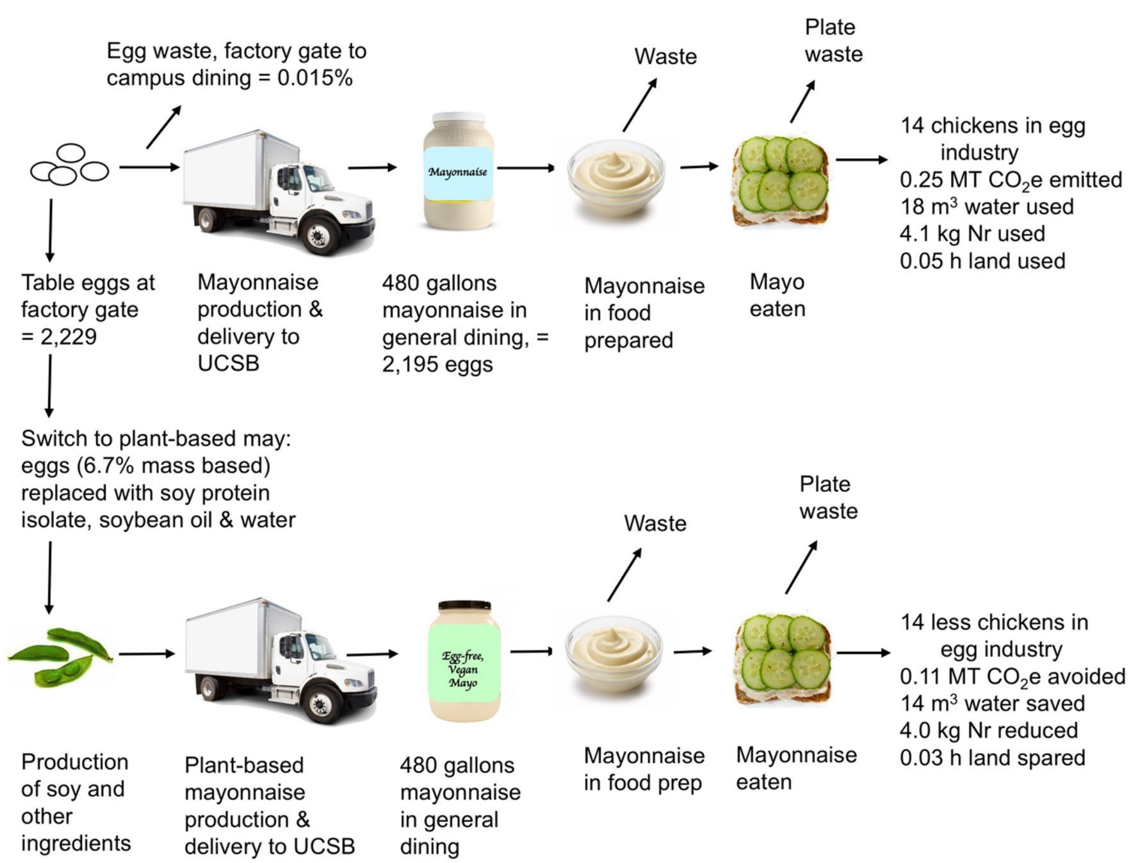

Fig. 3 Estimating the annual impact of switching to plant-based mayonnaise in UCSB general dining

Table 2 Impact of reduced egg consumption on animal welfare and the environment

Scenario, location	Eggs used $year^{-1}$ at institutional/retail level before change to plant-based alternatives			Net impact $year^{-1}$ of change to plant-based alternatives to eggs, cradle to farmgate, adjusted for waste				
				Chicken welfare (number of chicken in egg industry)[c]	Environmental impact[d]			
	Eggs at institution level[a]	Eggs at farm gate[b]	50% of eggs at farm gate		MT CO_2e	m^3 water	kg Nr	ha land
Plant-based mayonnaise replaces 100% of egg-based mayonnaise $year^{-1}$[e]								
UC Santa Barbara								
General dining[f]	2,195	2,229		– 14	– 0.11	– 13.70	– 3.99	– 0.03
Residential dining[g]	11,818	11,998		– 76	– 0.58	– 73.73	– 21.48	– 0.17
Total	14,013	14,227		– 90	– 0.68	– 87.42	– 25.47	– 0.20
UC, all campuses[h]	144,264	146,461		– 924	– 7.02	– 900.01	– 262.19	– 2.06
Tofu replaces 50% of all eggs used $year^{-1}$[i]								
On all UC campuses, only for first-year student breakfast[j]	2,885,365	2,929,305	1,464,652	– 9,245	– 85	– 8,213	– 2,627	– 22
On all UC campuses with spillover to all off-campus meals[k]	123,997,721	125,886,011	62,943,005	– 397,302	– 3,674	– 352,956	– 112,877	– 926
On all UC campuses with spillover to all off-campus household meals[l]	367,033,253	372,622,592	186,311,296	– 1,176,015	– 10,874	– 1,044,749	– 334,117	– 2,741
United States[m]	90,730,517,000	92,112,200,000	46,056,100,000	– 290,710,500	– 2,688,043	– 258,261,562	– 82,593,681	– 677,451

[a]For the mayonnaise scenarios the amount at institutional level was based on estimates of the amount of mayonnaise used and the amount of eggs in mayonnaise (see note e below). For UCSB the amount of mayonnaise used was based on purchase data, and for all UC campuses the amount was estimated based on the UCSB amounts per person. For the tofu scenarios the amount at institutional level was calculated from the amount at farm gate adjusted for a loss and waste rate of 1.5%. According to the USDA, in 2017 the loss and waste of based on amount available at the of farm gate was 1.5% to institution/retail, 8.9% at the institutional level, and 28.9% at the consumer level for a total of 39.3%

[b]For the mayonnaise scenarios, eggs at farm gate = the number of eggs produced that result in the number available at retail/institutional level after loss and waste (= 0.015%) (USDA ERS 2019a). For the tofu substitution scenarios, we calculated eggs cap^{-1} at farm gate by dividing the the total number of eggs produced Dec 2016-Nov 2017 (Table 1) by the US population in 2017 (USCB 2020); we then multiplied the result by the population for each scenario

[c]Estimated using 0.0063 chicken lives egg^{-1} (Table 1, Calculations)

[d]Estimates of environmental impact of eggs are for 2010 based on (Pelletier et al. 2014) and (Eshel et al. 2014) (Table S1). Estimates of environmental impact of replacing eggs in mayonnaise with soy protein isolate are based primarily on (Berardy et al. 2015; Braun et al. 2016; Eshel et al. 2014) (Table S2). Estimates of environmental impact of replacing eggs in the diet with tofu are based primarily on (Berk 1992; Eshel et al. 2014; Mejia et al. 2018) (Table S3)

[e]Estimate of number of eggs use in mayonnaise based on data for mayonnaise use from general and residential dining, assuming eggs = 6.7% of mass of mayonnaise (Sheldon et al. 2017, p. 29), and weight per egg is mean of the USDA largest + smallest size classes (53.15 g) (USDA AMS 2000). We assumed whole egg used in egg-based mayonnaise, as some use whole eggs plus egg yolks, and ingredient amounts are not available (Table S2). We assumed that eggs are 6.7% of mass of mayonnaise (Sheldon et al. 2017, p. 29) and are replaced by an equal combined mass of soy protein isolate, soybean oil and water in plant-based mayonnaise

[f]Assumes all people on campus except first-year students eat their meals with general dining

[g]Assumes academic year, and all first-year students eat all of their meals in residential dining

[h]Using estimates of meals eaten by UC population for fall 2018 (Table S4)

[i]Estimate of number of eggs used in the UC food supply based on the average number of eggs produced annually (Table 1), adjusted for loss and waste from farm gate to the institutional level of 1.5% based on USDA loss-adjusted food availability (LAFA) data (USDA ERS 2019a). Total eggs consumed includes eggs in shell as well as "processed" or "broken eggs," which comprise about one-third of the eggs consumed in the US, including as liquid, dried, or frozen eggs, for example as ingredients in food products. For on-campus meals we assumed eggs only eaten at breakfast, and therefore used only one meal day^{-1}, and only for first-year students, which underestimates egg consumption because of eggs used in ingredients for foods eaten at lunch and dinner. For spillover to off-campus meals, we used the total per capita egg consumption. We assumed

Table 2 (continued)

that eggs were replace by an equal mass of tofu, with environmental impacts based on (Mejia et al. 2018) and (Eshel et al. 2014); conversions from https://ussec.org/resources/conversion-table/ (Table S3)

[j]See Table S4 for estimates of number of meals per year on campus. Assumes = distribution of eggs among meals

[k]Assumes all 3 meals day^{-1} for entire year for total UC population, and total egg consumption

[l]Assumes household size including the UC person = mean for California 2013–2017: 2.96 persons. (https://www.census.gov/quickfacts/fact/table/ca/PST045217)

[m]See note i above for method used to estimate number of eggs in the US food supply. We used the US population for July 1, 2016 (323,071,342) (https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk)

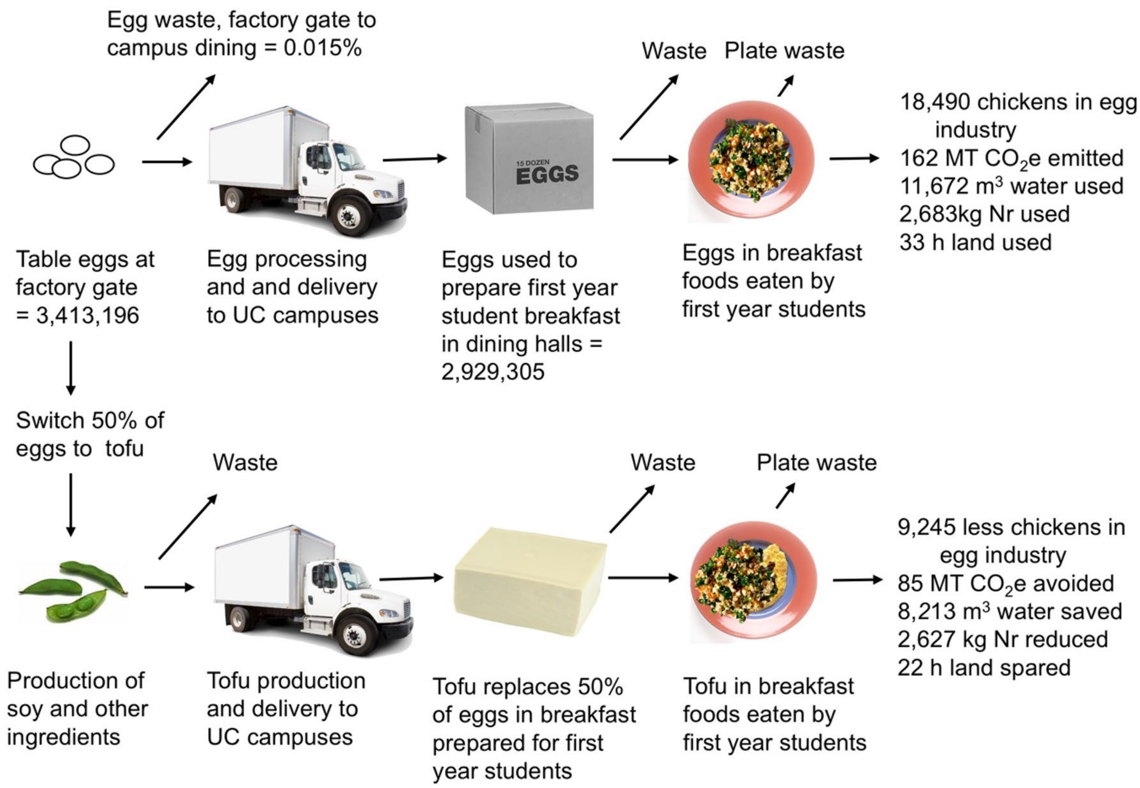

Fig. 4 Estimating the annual impact of substituting tofu for 50% of eggs consumed by first-year students at breakfast, on all UC campuses

Table 3 Percentage reduction of environmental impacts of eggs vs. egg substitutes

Environmental impact variable	Replacement of	
	Egg-based mayonnaise by plant-based mayonnaise (%)	Eggs by tofu (%)
Greenhouse gas emissions (kg CO_2e)	43	53
Blue water (L)	77	70
Reactive nitrogen (g Nr)	98	98
Land use (m^2)	63	65

Climate and other environmental impacts of the US egg industry have been decreasing in recent decades along with increasing efficiency (Pelletier et al. 2014). This has also been documented else where, for example, a meta-analysis of over 2,000 egg farms in the UK found that reductions in cumulative mortality were associated with reductions in environmental impacts, including GHGE and land use (Weeks et al. 2016). However, while increasing efficiency can decrease environmental impacts, it is often correlated with decreased chicken welfare, as discussed in the previous section.

Although efficiency improvements can reduce environmental impacts, the inherent biomass conversion factors associated with primary production (plants) to animal product production (eggs) means that plant-based alternatives are always likely to have a lower environmental impact. In the products we analyzed (soy protein isolate, soybean oil, and tofu), all environmental impacts were much lower than eggs, adjusted to match nutrient mass or calories. In contrast to decreasing environmental impact in the egg industry, which appears to be associated with decreased chicken welfare, our results show that substituting plant foods for eggs increases welfare *and* reduces environmental impact.

Strategies for scaling up the replacement of eggs with plant foods

Higher education institutions have the ability to alter physical, social, economic and informational food environments to support plant-based food choices, and have the purchasing power to effect the upstream food system to respond to those choices (Thottathil 2019). There have been a number of such initiatives on UC campuses (Cleveland and Jay 2020a).

The substitution of plant-based mayonnaise in our UCSB case study showed how food environments can change without active food choice by consumers. Change is more challenging when active choosing is required, as when tofu or other plant foods are substituted for eggs. One promising strategy is simply increasing the availability of plant based options to nudge people toward choosing those options without limiting their ability to choose animal foods. A study at a UK university found that increasing the availability of vegetarian meals from 25 to 50% increased their sales by 41–79%, decreased meat meal sales, and did not result in detectable rebound (increased meat meal sales elsewhere) (Garnett et al. 2019). Three experiments in Denmark found that making a vegetarian meal choice the normative default instead of the non-vegetarian choice increased the proportion of people choosing vegetarian meals during pre-conference registration from 2–12.5% to 86–89% (Hansen et al. 2019). There is also a growing advocacy campaign to promote this strategy in US higher educational and other institutional food settings, DefaultVeg (https://defaultveg.org/).

Choosing plant-based foods instead of eggs or other animal foods, including in nudging environments, would likely increase if information that motivated people to make this choice was provided through classes, signage and social media. For example, after a course at UC Los Angeles on the environmental impact of foods, students' self-reported food intake over all their meals showed a reduction in beef consumption and in greenhouse gas emissions compared with students in a control class (Jay et al. 2019), a single 50-min lecture, on the effect of food on climate and of meat on health, was associated with a switch by students from choosing meat-based to plant-based meals which lasted a full academic year (Jalil et al. 2020), and the food choices of university students in the UK were influenced by their perception of the eating habits of their social media peers (Hawkins et al. 2020). These type of information interventions would also likely increase the extent of spillover to off campus settings.

The UC's GFI is an example of the commitment of higher education institutions to improve the animal welfare, human and community health, and environmental sustainability of food on campus. Other UC initiatives have also been effective, for example substituting 30% plant burgers for 100% beef burgers (Jay et al. 2019). All of these changes are challenging because the current socioeconomic system incentivizes the sale of food that is profitable, but bad for animal welfare, the environment, human health and society, and allows the food industry to block changes to the status quo (Swinburn et al. 2019, p. 32). This is true on campuses, where pouring rights contracts with soda companies, fast food franchises, and unhealthy food often dominate food environments.

Conclusion

Our case study of substituting egg-based with plant-based mayonnaise in general dining at UCSB demonstrates that where staff and student advocates have improving animal welfare and environmental sustainability as goals, and when plant foods with similar price, and culinary and logistical characteristics can be identified, the substitution of plant foods for animal-source foods can be relatively easy.

To estimate the impact of this substitution we found the answer to our question, "How many chickens does it take to make and egg?" in the US egg industry, was 0.0063 chickens per egg. This is equal to 158 eggs per chicken, less than half the amount of eggs per laying hen because of mortality from hatching to entering the laying flock, including the disposal of all male chicks. We used this result to calculate the reduction in the number of chickens that would be subject to the poor welfare conditions in the industry when egg consumption is reduced. We also estimated environmental impacts, and found greenhouse gas emissions, irrigation water, reactive nitrogen (Nr), and land use would be reduced 43–98% from those of eggs.

While we found the impact of plant-based mayonnaise was relatively small because of the small proportion of mayonnaise in the diet, we showed that the substitution of eggs consumed with tofu would have a much greater impact. For example, substituting 50% of eggs with tofu in first-year student breakfasts on all UC campuses would reduce the number of chickens in the egg industry by 9,245. If this substitution was made for the US population, the welfare and environmental benefits would be 29 thousand times greater.

Substituting tofu or other plant foods for eggs would require more participation by consumers, and therefore more education and other information and changes in the food environment, including creative choice nudging. These strategies are beginning to be implemented at the UC, many other higher education institutions, and beyond.

The positive effect of reducing egg consumption on chicken welfare would be large even if welfare certified eggs are replaced, since the requirements of the most commonly used chicken welfare certification programs do relatively little to reduce chicken suffering. That is, given the history of the egg industry dominated by the profit motive, it is not likely that negative welfare impacts of egg production will decrease substantially in the near future unless egg consumption decreases. In fact, the trend of increasing efficiency to increase profits, measured as reduced number of chickens required to produce an egg, is likely to decrease chicken welfare even as it decreases environmental impact.

This means that decreasing egg consumption (and production) and replacing eggs with plant foods is the most effective way to increase chicken welfare, while also producing large environmental benefits. Plant-based substitute foods can also provide the nutritional benefits of eggs in the diet and omit most of the harmful environmental effects.

Our calculations can help advocates of increasing the animal welfare and environmental, climate, health and social benefits of diet change to quickly estimate the impact of existing and potential programs and policies for replacing eggs with plant foods. Our methods included assumptions that make our results conservative. Data collected by university dining services provide the basis for documenting these benefits, including contributing to campus health and sustainability policy goals. This information could in turn provide additional incentives for individuals, higher education institutions, and others to make needed changes in the food system.

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Supplementary Information

TITLE: How many chickens does it take to make an egg? Animal welfare and environmental benefits of replacing eggs with plant foods at the University of California, and beyond

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S1. Impact of reduced egg consumption on the environment

S1.1. Environmental impact of egg consumption

Table S1 presents the environmental impact of eggs across the four metrics we considered: GHG emissions, blue water (irrigated), reactive Nitrogen (fertilizer inputs), and land area (feed crops only). s

Table S1 Environmental impact of eggs. Bold = variable values used in Table 2.

Variable	Value	Source
g egg^{-1}	53.16	(USDA ERS 2018)
kg egg^{-1}	0.05316	calculated
edible Mcal (kg egg)$^{-1}$	1.43	(USDA ARS 2018), item 01123
Greenhouse gas emissions		
kg CO_2e (edible Mcal)$^{-1}$ (mean)	1.45	(Eshel et al. 2014)
kg CO_2e (kg egg)$^{-1}$, value 1, up to farm gate, only feed	2.08	(Pelletier et al. 2014) See table 12
kg CO_2e egg^{-1}	**0.11056**	
Blue water (irrigation) y^{-1}		
L Mcal^{-1} (mean)	104.84	(Eshel et al. 2014)
L kg^{-1} (calculated)	149.93	calculated
L egg^{-1}	**7.97**	
Reactive N (Nr) y^{-1}		
g Nr Mcal^{-1} (mean)	24.10	(Eshel et al. 2014)
g Nr kg^{-1} (calculated)	34.47	calculated
g Nr egg^{-1} (calculated)	**1.83**	calculated
Land area y^{-1}		
m^2 Mcal^{-1} (mean)	2.96	(Eshel et al. 2014)
m^2 kg^{-1}	4.23	calculated
m^2 egg^{-1}	**0.22**	calculated

S1.2. Environmental impact of egg-equivalent substitution of egg in mayonnaise

Table S2 presents the environmental footprint of an egg-equivalent substitution as estimated for the plant-based mayonnaise, represented by the term "mayosub". In assessing a likely substitution that would match some of the nutrient profile of egg materials used in mayonnaise, we assumed a mayosub would be made of 14% soy protein isolate (SPI), 21% soybean oil, and the remaining 64% to be water. This is relatively consistent with the protein, fat, and water content of an egg, with a mayosub having a slightly higher fat content to account for yolks (eggs are about 14% protein, 10% fat, and 76% water).

Table S2 Environmental impact of egg substitute for mayonnaise (“mayosub”). Bold = variable values used in Table 2.

Variable	Value	Source
g mayosub^{-1}	0.00	Assumed to match mass of eggs
g SPI (mayosub)$^{-1}$	7.6	calculated to match protein in eggs
g soybean oil (mayosub)$^{-1}$	11.4	calculated to approximate fat in mayonnaise
g water (mayosub)$^{-1}$	34.2	calculated to approximate water in eggs
kg soybean (kg mayosub)$^{-1}$	3	Assumed ratio of soybean input
Greenhouse gas emissions		
kg CO_2e (kg SPI)$^{-1}$	2.4	(Braun et al. 2016)
kg CO_2e (kg soybean oil)$^{-1}$	3.9	(Poore and Nemecek 2018)
kg CO_2e mayosub^{-1}	**0.063**	Calculated from mass of SPI and Soybean Oil
Blue water (irrigation)		
L kg SPI^{-1} (processing)	30.0	(Berardy et al. 2015)
L kg soybean^{-1} (irrigation)	70.4	calculated from (Eshel et al. 2014)
L mayosub^{-1}	**1.8**	calculated
Reactive N (Nr)		
g Nr (kg dry soybean)$^{-1}$	1.85	calculated from (Eshel et al. 2014)
g Nr mayosub^{-1}	**0.042**	calculated
Land area		
bushels m^{-2}	40	(Eshel et al. 2014)
m^2 (kg SPI)$^{-1}$	11.15	calculated
m^2 mayosub^{-1}	**0.084**	calculated

GHG emission intensities used were from immediate values presented in sources. Water inputs for SPI were taken to be derived from processing and irrigation of soybeans. For irrigation water, we attribute all water from soybeans to be accounted in SPI, although remaining soybean matter used for SPI has other uses. For this reason, we did not attribute water to soybean oil production to eliminate double counting. Of particular note is the blue water (irrigated) use for soybeans, which is highly variable. Many farms are not irrigated at all, while some farms have high amount of irrigation. Because we attribute all water in soybean production to a mayosub, the water estimate is conservatively high.

Finally, land and Nr were taken from application of Nr and use of land for growing dry soybeans only. For SPI output per unit soybean input, we assumed a ratio of three units soybean mass per unit SPI.

S1.3. Environmental impact of substitution of tofu for eggs in the diet

Table S3 presents the environmental footprint of an egg equivalent in terms of tofu, represented by the term “tofusub”. A tofusub is an equal tofu equivalent of an egg by mass. USDA data show that, by mass, tofu has about the same caloric content (143 kcal per 100g eggs and 144 kcal per 100 g tofu), so a caloric substitution vs. a mass substitution do not substantially differ. Tofu has a higher protein content (17.3 g protein per 100 g tofu vs. 12.6 g protein per 100 g eggs), but a slightly lower fat content. Substituting tofu for eggs on a protein basis would thereby make its environmental impact even lower.

Table S3. Environmental impact of egg substitute in diets ("tofusub"). Bold = variable values used in Table 2.

Variable	Value	Source
g tofu (tofusub)$^{-1}$	53.16	assumed to match mass of eggs
g dry soybean (g tofusub)$^{-1}$	0.394	calculated from (Mejia et al. 2018)
Greenhouse gas emissions		
kg CO_2e (kg tofu)$^{-1}$	0.982	(Mejia et al. 2018)
kg CO_2e tofusub^{-1}	**0.052**	calculated
Blue water (irrigation)		
L (kg tofu)$^{-1}$ (processing)	16.7	(Mejia et al. 2018)
L (kg soybean)$^{-1}$ (irrigation)	70.4	(Eshel et al. 2014)
L (kg tofu)$^{-1}$ (irrigation)	27.8	calculated
L (kg tofu)$^{-1}$	44.4	calculated
L tofusub^{-1}	**2.4**	calculated
Reactive N (Nr)		
g Nr (kg dry soybean)$^{-1}$	1.85	calculated from (Eshel et al. 2014)
g Nr tofusub^{-1}	**0.039**	calculated
Land area		
Bushels acre^{-1}	40	(Eshel et al. 2014)
kg dry soybean bushel^{-1}	27.2	calculated
m^2 (kg dry soybean)$^{-1}$	3.72	calculated
m^2 tofusub^{-1}	**0.078**	calculated

S2. University of California population and meals eaten

Table S4 University of California campus population, meals eaten.

Population category	Population size, 2018	Number of meals yr^{-1} eaten by UC population		
		On campus[a]	On & off campus[b]	On & off campus, and 1.96 other family members[c]
First year student enrollment[d]	46,677	34,027,533	51,111,315	151,289,492
Non-first year student enrollment[e]	239,594	41,586,673	262,355,430	776,572,073
Total student enrollment[f]	286,271	75,614,206	313,466,745	927,861,565
Faculty and staff FTE[g]	158,876	38,130,288	173,969,439	514,949,539
Total UC population	445,147	113,744,494	487,436,184	1,442,811,105

[a]Assumes: for first year enrollees, 3 meals d^{-1}, 243 days (academic yr)$^{-1}$ based on UCLA dining hall schedule, no snacks; for non-first year enrollees, 1 meal d^{-1} (lunch), 174 days (academic yr)$^{-1}$; for staff and faculty, 1 meal d^{-1} (lunch), 5 days wk^{-1}, 48 weeks yr^{-1}. These numbers don't include meals eaten by visitors, summer program participants, or attendees at sport, entertainment or other special events.

[b]Assumes 3 meal d^{-1}, 7 days wk^{-1}, 365 days yr^{-1}.

[c]Assumes a household size including the UC person = average for California 2013-2017: 2.96 persons. (https://www.census.gov/quickfacts/fact/table/ca/PST045217)

[d]Data from https://www.universityofcalifornia.edu/infocenter/freshman-admissions-summary.

[e]Total enrollment minus first year enrollment.

[f]Data from https://www.universityofcalifornia.edu/infocenter/fall-enrollment-headcounts

[g]Academic + non-academic employees, data from https://www.universityofcalifornia.edu/infocenter/uc-employee-headcount. Assumed each FTE ate lunch 5 days wk^{-1}, 48 weeks yr^{-1}.

S3. References

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