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Cheese without cows: Consumer demand for animal-free dairy cheese made from cellular agriculture in the United Kingdom

RESEARCH ARTICLE

Peter Slade[a] and Oscar Zollman Thomas[b]

[a]*Associate Professor, Canadian Canola Growers Association Agricultural Policy Chair, Department of Agricultural and Resource Economics, University of Saskatchewan, 51 Campus Drive, Saskatoon, SK, Canada S7N 5A8*

[b]*Analyst, Formo, Stralauer Allee 10-11, 10245 Berlin, Germany*

Abstract

We examine consumer demand for animal-free dairy cheese produced using cellular agriculture. Our data is generated through a hypothetical choice experiment completed by 1249 UK residents. Using a mixed logit model, we predict that animal-free dairy cheese would have a conditional market share of 22% when priced at a 25% markup relative to premium conventional cheese. However, the market share is quite sensitive to price: only 2% of consumers would purchase animal-free dairy cheese if it were twice the price of premium conventional cheese. Three-quarters of consumers who purchase animal-free dairy cheese would have purchased conventional dairy cheese if animal-free dairy cheese were unavailable. We use our experimental results to examine the impact of higher conventional dairy cheese prices, such as those that might result from a tax on livestock products. We find that the introduction of animal-free dairy cheese reduces consumer losses from higher conventional dairy prices by about 20%.

Keywords: cellular agriculture, dairy alternatives, discrete choice experiment, lab-grown cheese, plant-based cheese
JEL code: D12, Q18

Corresponding author: peter.slade@usask.ca

1. Introduction

The role of industrial animal agriculture is increasingly prominent in discussions about climate change, animal welfare, and human health (Bonnet *et al.*, 2020). Livestock is responsible for 14.5% of global greenhouse gas (GHG) emissions and 5% of emissions in the United Kingdom (UK) (Department for Environment Food & Rural Affairs, 2021; Gerber *et al.*, 2013; Ritchie and Roser, 2013). Within the UK, there are serious discussions about reducing livestock emissions as the country strives for carbon neutrality by 2050 (Government of the United Kingdom, 2021; Gatten, 2021).

Concerns about the impact of livestock production have led to an increased interest in alternatives to meat and dairy products (Government of the United Kingdom, 2021). Global sales of plant-based products are growing rapidly, although they remain small compared to overall sales of livestock products. The Good Food Institute (2021) reported that in 2020 US sales of plant-based milk were $2.5 billion, sales of plant-based meat were $1.4 billion, and sales of plant-based cheese were $270 million. In comparison, the Bureau of Labour Statistics (2021) finds that sales of fresh milk and cream were $19.3 billion and sales of meat were $132 billion (these figures only account for food consumed at home). According to one estimate, sales of plant-based milk and meat alternatives in the United States (US) now exceed $7 billion (Good Food Institute, 2021). Alae-Carew *et al.* (2022) also show a dramatic increase in the number of UK consumers who purchased plant-based alternatives between 2009 and 2018.

Despite the small market share of livestock substitutes, a substantial minority of omnivores appear open to reducing their livestock consumption (Graça *et al.*, 2015; Malek *et al.*, 2019). The most significant barrier to further adoption of plant-based products is taste; a wide body of research finds that omnivores are considerably more likely to adopt livestock alternatives that emulate the taste and texture of livestock products (Elzerman *et al.*, 2011; Michel *et al.*, 2021).

Cellular agriculture holds the promise of creating foods that have the same sensory appeal as livestock products, while avoiding the use of animals. Rather than formulating plant proteins to taste like animal products, cellular agriculture employs synthetic biology, tissue engineering, and/or molecular biology to produce ingredients that are compositionally identical to animal-derived products. Investment in research and development of cellular agricultural products has increased considerably in the past decade (Keerie, 2021). However, it remains to be seen whether consumers will adopt these products and whether these adopters will reduce their consumption of livestock-derived foods.

In this paper, we examine consumer demand for *animal-free dairy cheese* produced through precision fermentation, a branch of cellular agriculture in which specific proteins or fats are produced by microorganisms. Our primary objectives are to estimate the potential market share for animal-free dairy cheese and to analyze the relationship between demand for animal-free dairy cheese, conventional dairy cheese, and plant-based cheese.

We note that the term "animal-free dairy" is not without controversy, as "dairy" has typically been used to refer to foods that are produced with mammalian milk. However, "animal-free dairy" is used to market existing products and appears to be the standard terminology in academia (Broad *et al.*, 2022; Hettinga, 2022; Loike, 2022; Waltz, 2022), the popular press (Bandoim, 2018; Levitt, 2016; Mack, 2019), and industry (ADM, 2022; Nestle, 2022; Perfect Day, 2022).

To our knowledge, there are no existing estimates of the potential market share for animal-free dairy. In contrast, there is a significant amount of research investigating consumer adoption of cultivated meat (Bryant *et al.*, 2019; Bryant and Barnett, 2020). The relative lack of interest in dairy products produced via cellular agriculture is surprising as the dairy sector has a substantial environmental footprint, and dairy products produced via cellular agriculture are closer to widespread commercialization than cultivated meat products (Morach *et al.*, 2021).

We estimate consumer preferences using a mixed-logit model. The model is estimated on data from a hypothetical discrete choice experiment in which consumers choose between animal-free dairy cheese, nut-based vegan cheese, and three types of conventional dairy cheese. We use these estimates to examine three interrelated questions.

First, we predict the share of consumers who would purchase animal-free dairy cheese and analyze how the introduction of animal-free dairy cheese impacts the market share of conventional cheese. Given that animal-free dairy cheese is not yet widely commercialized, we pay particular attention to how the price of this product will impact market shares. Second, we estimate the price elasticities of market shares, revealing the degree of substitutability between different types of cheese. Finally, we examine how animal-free dairy cheese moderates the impact of higher conventional cheese prices, which could result from production shocks or taxes on livestock products (Bonnet et al, 2020).

2. Background

In this section, we overview the production and marketing of conventional, plant-based, and animal-free dairy cheese.

2.1 Conventional dairy cheese

In 2018, the UK produced 470 000 ton of cheese and consumed 790 000 ton. This amounts to 11.9 kg of cheese consumed per person (Food and Agricultural Organization, 2021). UK dairy production requires 1.9 million dairy cows and creates a substantial amount of greenhouse gas emissions, primarily through methane released during the digestive process of cattle (Department for Environment, Food and Rural Affairs, 2022). In Appendix A, we survey estimates of the emissions factors from cheese production. These factors range from 4.68 to 12.12 kg of carbon dioxide equivalent (kg of CO_2e) per kg of cheese, with a median of 6.70. The wide range of estimates is due to factors such as ripening time, protein density, country of origin, and type of cow (Aguirre-Villegas *et al.*, 2011). Based on the median emission factor, the average UK consumer's cheese consumption creates 79.73 kg of CO_2e. Collectively, this is equal to 1.2% of GHG emissions in the UK (Department for Business, Energy and Industrial Strategy, 2020). In addition to climate change impacts, dairy production is a significant source of eutrophying emissions and uses substantial amounts of land and water (Steinfeld *et al.*, 2006).

2.2 Plant-based cheese

Several plant-based vegan cheese alternatives are currently available. Grossmann and McClements (2021) survey the ingredients and nutritional information of several popular cheese alternatives. The most common primary ingredients in these products are cashews, almonds, soy, and coconut oil. The nutrient profile of plant-based cheese alternatives is markedly different from dairy cheese, with many alternatives containing no protein or calcium. After detailing different methods for producing plant-based cheese, Grossman and McClements (2021) remark that a major challenge for these products is mimicking the complex structure of dairy proteins. Similarly, Short *et al.* (2021) note that plant-based cheese alternatives have not been able to emulate the taste and mouthfeel of conventional cheese. Although the number and quality of plant-based cheese alternatives continues to grow, their market penetration remains low compared to plant-based meat and milk alternatives (Alae-Carew *et al.*, 2022).

To our knowledge, no academic studies have examined the GHG emission factors for plant-based cheese alternatives; however, the primary ingredients in these products have emissions factors that are well below those of conventional dairy cheese (Grossmann and McClements, 2021). A life-cycle assessment commissioned by Violife, a plant-based cheese company, found that the production of its plant-based mozzarella (made predominantly of coconut oil and starches) resulted in 79% less greenhouse gas emissions, 84% less land use, and 52% less water use compared to conventional mozzarella (Quantis, 2022).

We are not aware of any existing estimates of potential market shares for plant-based cheese. There is a small literature that examines plant-based milk, which experienced rapid growth in demand after 2010. Slade (2023) finds that when households increase their purchases of plant-based milk by one gallon, they reduce their dairy milk consumption by 0.43 to 0.60 gallons. Slade and Markevych (2023) find that plant-based milk sales are higher among women and younger individuals. Conversely, sales are lower among individuals with food neophobia and those who value taste and tradition. The same sociodemographic characteristics and attitudes impact the consumption of plant-based meat (Elzerman *et al.*, 2015; Hoek *et al.*, 2004; Schösler *et al.*, 2012; Siegrist and Hartmann, 2019; Slade, 2018b).

2.3 Cellular agriculture and animal-free dairy cheese

Cellular agriculture products can be categorized as either cellular or acellular. Cellular products, such as cultivated meat, are derived from live or formerly live cells, and these cells are used in the final product. In contrast, acellular products — such as animal-free dairy cheese — harness cells to produce specific proteins or fats, which are then separated from the cells themselves. In the case of animal-free dairy cheese, precision fermentation is used to produce whey and casein, key components in dairy products.

Producing animal-free dairy cheese with precision fermentation involves six main steps: strain engineering, fermentation, harvesting, combining, coagulating, and forming. The first step is to determine the DNA sequences responsible for milk protein production and transpose a copy of these sequences into a host microorganism, allowing them to synthesize milk proteins. These microorganisms are then transferred to large-scale fermentation tanks similar to those used in beer production, where conditions and feed are optimized for milk-protein production. After a number of days, the fermentation broth is collected and finely filtered to extract the protein. This protein is then combined with fats, salts, and carbohydrates to create a concentrate that serves as the basis for cheese and other dairy products. As in traditional cheese production, fermentation enzymes or heat are used to coagulate this mixture into a curd, which can then be immediately packaged as fresh cheese or ripened to create stronger, firmer cheeses.

Animal-free dairy ice cream and cream cheese are currently available in limited quantities in US locations (Perfect Day, 2022), and several companies are in the process of bringing animal-free dairy cheese to market. Two recent life-cycle analyses have examined the emissions impacts of animal-free dairy protein (specifically, the two studies examine recombinantly produced beta-lactoglobulin made in *Trichoderma reesei*). A study by Perfect Day (an animal-free dairy producer) found that GHG emissions from their product were 91–97% less than emissions from protein produced via cows (Perfect Day, 2021). In a hypothetical analysis, Behm *et al*. (2022) estimate that emissions from producing animal-free dairy protein would be 50–100% of the emissions from conventionally produced dairy protein in New Zealand. These two studies note that emissions from annual-free dairy production depend on several critical factors, including the source of energy, the raw materials used as feedstock, the yield of microorganisms, the efficiency of down-stream processing and the allocation of emissions to by-products. This latter factor accounts for much of the difference in estimated emissions between the two studies.

As cellular agriculture is still in its infancy, it is difficult to project the impact of economies of scale, production optimization, and new innovations. Järviö (2021) note that energy emissions (the largest source of emissions in the production of animal-free dairy products) can be reduced by sourcing energy from renewable sources or locating production facilities in areas with clean energy. Similarly, a variety of feedstocks can be used for microbial growth, with varying climate impacts (Hamdan and Senez, 1992). Linder (2019) even notes the potential for carbon-negative feedstocks. Under most assumptions, however, substantially less land and water are required to produce cellular agricultural products compared to livestock-derived products (Tuomisto, 2022).

We are not aware of any studies that directly compare the environmental footprint of plant-based dairy alternatives and animal-free dairy products. Most studies agree that the carbon footprint of cellular agricultural products is considerably higher than products from plant-based sources (Tuomisto, 2022). However, these studies generally do not consider emissions from processing plant-based sources into a final product, such as plant-based cheese. The ultimate environmental impact of animal-free dairy depends on the extent to which it can be produced with lower emissions than livestock-derived products and the extent to which it substitutes for livestock-derived products instead of plant-based alternatives.

Zollman-Thomas and Bryant (2021) explore consumer willingness to adopt animal-free dairy cheese in five countries. In their sample, 79% of consumers are willing to try animal-free dairy cheese, with significant variation between the countries sampled. This is notably higher than consumers' willingness to try cultivated meat (Bryant and Barnett, 2020).

While there has been relatively little research examining consumer perceptions of animal-free dairy, considerable attention has been paid to understanding consumer demand for cultivated meat. Several studies show that cultivated meat appeals to consumers who are younger and more educated consumers (Mancini and Antonioli, 2019; Slade, 2018b; Weinrich *et al.*, 2020), and to omnivores more than to vegetarians or vegans (Bryant and Dillard, 2019; Mancini and Antonioli, 2019; Valente *et al.*, 2019; Wilks and Phillips, 2017).

3. Materials

To analyze the potential market for animal-free dairy cheese, we conducted a survey and a discrete choice experiment that was completed by 1,249 UK respondents. This study received ethical approval from the Psychology Research Ethics Committee of the University of Bath. Participants used a checkbox on the questionnaire to indicate their informed consent in accordance with the Declaration of Helsinki.

3.1 Participant recruitment and screening

Participants were recruited through the SurveyGo research panel. Panelists were sent a general email asking if they would like to participate in a survey. After answering questions about their age and gender, qualified participants were routed to the survey. We used four interlocking quotas to ensure that the sample was representative of the age and gender of the UK population. Participants who completed the experiment received a redeemable points incentive, equivalent to roughly £1.50.

Participants were removed from the study if they did not provide their consent or failed one of two attention checks included in the survey. The first attention check required participants to spend at least 15 seconds on the screen containing a 160-word description of precision fermentation manufacturing methods. The second check required participants to select one option from a list of five possibilities. We also deleted observations in which responses to text input questions were either non-sensical or repeated across multiple questions. These responses were likely generated by inattentive participants or bots.

3.2 Information

To avoid using the term "cheese", which the EU restricts to products made with mammalian milk, the experiment refers to the animal-free dairy cheese product by the brand name "Legendairy" (see EU regulation 1308/2013). Respondents were provided an information script (contained in Appendix B) that outlined the production method. The information script advised participants that animal-free dairy cheese would taste and behave the same as conventional cheese while having a lower carbon footprint.

3.3 Experiment

In the discrete choice experiment, participants faced ten different choice tasks. In each task, participants could choose between six options: nut-based mozzarella, premium mozzarella, ball mozzarella, block mozzarella, animal-free dairy (i.e. Legendairy) mozzarella, or not purchasing. A sample choice question is shown in Figure 1. All cheese products weighed 200 g.

Cheese prices were drawn from a discrete set of prices, which are displayed in Table 1. These prices were based on the range of cheese prices observed in UK supermarkets. As there is uncertainty about the eventual retail price of animal-free dairy cheese, a wider range of prices was chosen for this product. We created 30 different choice tasks with prices randomly drawn from the discrete distribution of prices. Respondents were shown ten random choice tasks from this set of 30.

As our primary focus is estimating market shares for different cheese types, the choice experiment did not specify any product attributes other than the type of cheese (e.g. ingredients, brand, country of origin, and environmental labels). When attribute levels are missing, respondents may make inferences about the levels of missing attributes across different products (Islam *et al.*, 2007; Kardes *et al.*, 2004). The predicted demand for animal-free dairy cheese will be understated (or overstated) if consumers infer that the animal-free dairy product has negative (or positive) attributes that are not inherent in the product. For example, respondents might derive positive utility from locally produced cheese and believe that premium cheese is more likely to be locally produced than animal-free dairy cheese. In this case, respondents' relative willingness to pay for premium cheese relative to animal-free dairy cheese will be overstated if the two cheese types share the same origin.

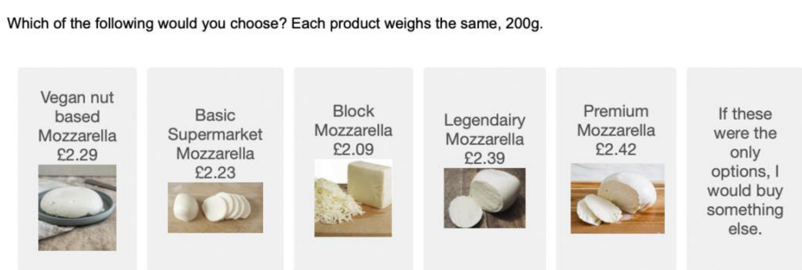


Figure 1. Sample choice task.

Table 1. Distribution of cheese prices.

Product (200 g)	Set of prices (£)
Animal-free dairy mozzarella	{2.39, 3.70, 5.02, 13.50}
Nut-based mozzarella	{2.29, 3.09, 3.89}
Premium mozzarella	{1.79, 2.42, 3.04}
Ball mozzarella	{1.31, 1.77, 2.23}
Block mozzarella	{1.61, 2.09, 2.58}

4. Data

Descriptive statistics of the data are contained in Table 2. The sampling scheme used four broad age quotas. However, the distribution of the sample diverged from the population when more granular age categories are considered (e.g., the number of 18–25-year-olds in our survey was below the proportion in the UK adult population). All of our descriptive statistics and subsequent analyses employ weights that reflect the age and gender of the UK population. Before completing the choice survey, respondents were asked if they would consider purchasing animal-free dairy cheese: 65% of respondents said they probably or definitely would, 22% said they might, and 14% said they would probably not or definitely not. In Table 2 we divide the sample into those willing to purchase animal-free dairy cheese and those who are unwilling or unsure. Zollman-Thomas and Bryant (2021) provide a deeper exploration of these descriptive statistics.

Table 2. Descriptive statistics.

	Full sample	**Willingness to purchase animal-free dairy cheese**	
		Unwilling/unsure	**Willing**
Willing to purchase animal-free dairy cheese?			
Definitely not	4.75%	13.5%	0%
Probably not	8.53%	24.3%	0%
Might or might not	21.8%	62.2%	0%
Probably yes	38.1%	0%	58.7%
Definitely yes	26.8%	0%	41.3%
Diet			
Cheese consumption per month[a]	16.1	11.3	19.6***
Vegan	1.71%	1.53%	1.83%
Vegetarian	4.62%	3.31%	5.55%*
Flexitarian/pescatarian	18.9%	9.82%	25.3%***
Omnivore	72.3%	82.5%	65.2%***
Other diet (than the four above)	2.43%	2.80%	2.16%
Sociodemographic characteristics			
Age	45.7	48.2	43.9***
Education[b]	3.12	3.15	3.09
Female	0.506	0.509	0.504
Income[c]	2.13	2.08	2.17
Liberal political orientation[d]	3.10	3.02	3.16***
Urban index[e]	2.18	2.21	2.17***

Weighted mean values (or percentages) with standard deviations in parentheses. *, **, *** denote statistically significant differences in mean values or percentages between the second and third columns at the 10%, 5%, and 1% levels.

[a] Sum of consumption of hard mozzarella, soft mozzarella, ricotta, vegan cheese, soft cheese, hard cheese, blue cheese, and pre-grated cheese. Respondents were asked to rate their consumption of each cheese on a six-point scale. We convert this into time eaten per month in the following manner: 0=Never purchase or less than once per month; 2=Less than once per week; 8=1–3 times per week; 20=4–6 times per week; 30=every day.

[b] 1=Secondary School, 2=Sixth Form/College, 3=Some university, no degree, 4=Undergraduate degree, 5=Master's degree, 6=Professional or doctorate degree.

[c] 1=Less than £25 000, 2=£25 000–49 999, 3=£50 000–74 999, 4= £75 000–99 999; 5=£100 000–124,999, 6=£125000 or more.

[d] 1=Lives in rural area, 2=Lives in town, 3=Lives in city.

[e] 1=Very conservative, 2=Somewhat conservative, 3=Moderate, 4=Somewhat liberal, 5=Very liberal.

On average, respondents consume cheese 16 times a month. Higher levels of cheese consumption are associated with a greater willingness to try animal-free dairy cheese. Of the respondents, 1.7% reported having a vegan diet, 4.6% a vegetarian diet, and 18.9% a flexitarian diet (defined as making an effort to only occasionally eat meat). Respondents' food consumption is not always consistent with their stated diet: 84% of self-reported vegans eat cheese, although most consume it infrequently. Interestingly, vegetarians or flexitarians are more willing to consume animal-free dairy cheese; however, vegans are not.

5. Model

Our primary analysis involves data from our choice experiment. To model consumer preferences, we assume that the utility the *i*th individual receives from the *j*th type of cheese is,

$$u_{i,j}(p_j, z_i; \beta_i) = \beta_{0,i,j} + \beta_1 p_j + \beta_{2,j} z_i + e_{i,j}, \tag{1}$$

where p denotes price; z denotes the individual-specific diet and sociodemographic variables listed in Table 2; and β are parameters to be estimated. Allowing that the error term follows a Gumbel distribution, and the individual receives zero utility from not purchasing a product, the probability of purchasing the *j*th cheese is

$$\Pr_i\left(\text{choice} = j, p, z_i; \beta_i\right) = \frac{\exp\left(u_{i,j}(p_j, z_i; \beta_i)\right)}{1 + \sum_{k \in C} \exp\left(u_{i,k}(p_k, z_i; \beta_i)\right)}, \tag{2}$$

where C is the set of all cheese types.

Without the individual subscripts on β_0, we could estimate equation 2 with a standard multinomial logit model. However, this model assumes the independence of irrelevant alternatives. Under this assumption, the introduction of a new cheese would have the same relative impact on the market share of all other cheeses. In reality, the introduction of animal-free dairy cheese is likely to have a relatively greater impact on the market shares of certain cheeses (e.g., nut-based cheese).

To relax this assumption, we allow the constant terms in each utility function to be randomly distributed according to a multivariate normal distribution. This allows (though does not impose) a correlation in the utility individuals receive from different cheeses. For example, individuals with stronger preferences for animal-free dairy cheese could also have stronger preferences for nut-based cheese.

The mixed logit model is estimated by maximizing a simulated likelihood function. To estimate this likelihood, we draw 500 sets of random coefficients from the multivariate distribution using a Sobel sequence. For each draw, we calculate the probability that the individual makes their observed choices and average across these probabilities. The individual simulated likelihood is

$$l_i(\Omega) = \frac{1}{500} \sum_{r=1}^{500} \left(\prod_{c=1}^{10} \Pr_i\left(\text{choice} = j_c^*, p_c, z_i; \beta_r(\Omega)\right)\right), \tag{3}$$

where r indexes the draws, c indexes the 10 choice tasks that each individual faces, j_c^* denotes the actual choice the individual made in the cth choice task, p_c denotes the prices in the cth choice task, and Ω denotes the vector of parameters that determine the distribution of the coefficients in the data (i.e. this vector holds the means of the random variables, the variance-covariance matrix, and the non-random parameters). These individual likelihoods are then logged and summed together to obtain the overall log-likelihood. We use the Apollo package in R to estimate the model (Hess and Palma, 2019).

5.1 Predicted market shares, elasticities, and marginal effects

After estimating the model, we contextualize our results by predicting market shares for each cheese type, calculating the elasticity of these market shares with respect to prices, and computing the marginal effect of the explanatory variables on these market shares. We use the median prices in Table 1 as the base prices for all our cheese types except animal-free dairy cheese, which we price at £3.00 per 200 g. Admittedly, the eventual market price of animal-free dairy cheese is uncertain. The price will depend on the market power of producers, the premium that consumers are willing to pay, and costs of production. To our knowledge, the only animal-free dairy cheese currently available is a cream cheese priced at 10 USD (£7.51) for a 226 g unit (Modern Kitchen, 2021). This price will likely decrease over time as more companies enter the market and production costs fall. Considering the uncertainty around the price of animal-free dairy cheese, we examine the sensitivity of our predicted market shares to changes in this price.

Predicted market shares are calculated by averaging across 500 draws of the random intercepts:

$$\mathrm{MS}_j(\hat{\Omega}) = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{500}\sum_{r=1}^{500}\mathrm{Pr}_i\left(\text{choice} = j, \bar{p}, \mathrm{z}_i; \hat{\beta}_r\left(\hat{\Omega}\right)\right), \tag{4}$$

where r indexes over the random draws, $\hat{\beta}_r$ is the set of parameters including the rth random draw of the intercepts, $\bar{p}$ is the vector of base prices, and N is the number of individuals in the data. For each draw of the intercepts, we predict the probability individuals in the data would purchase each product, $\mathrm{Pr}_i\left(\text{choice} = j, \bar{p}, \mathrm{z}_i; \hat{\beta}_r\left(\hat{\Omega}\right)\right)$, using equation 2. We then average across the draws and across the individuals in our data to obtain the market share.

To obtain the elasticity of the market share of the ith product with respect to the price of the jth product, we predict the market share of the ith product when the price of the jth product is 10% above its base price. The elasticity is equal to the percentage change in the market share of the ith product relative to its market share under the base prices divided by 10% (i.e. the percentage change in price).

The marginal effects of the explanatory variables (i.e. diet and sociodemographic characteristics) on market shares are calculated numerically. For continuous variables, the marginal effect of the variable of interest is the difference between the predicted market shares at the observed levels of the explanatory variables and the predicted market shares with the variable of interest increased by one unit for all respondents (holding all other variables constant). The marginal effect for binary variables is the difference between the market share with the variable of interest set equal to one and the market share with the variable of interest set equal to zero.

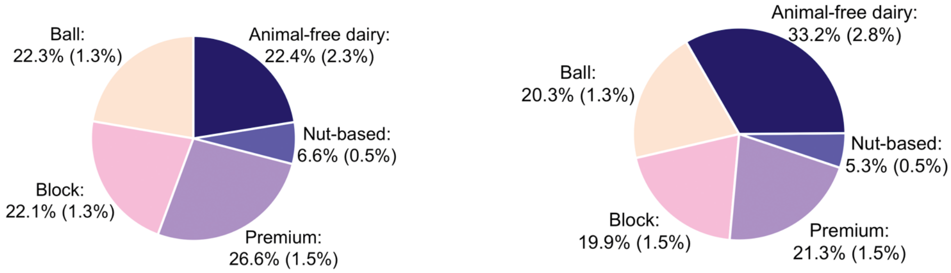
We generate standard errors for market shares, elasticities, and marginal effects numerically. To estimate these standard errors, we redraw the estimated coefficients ($\hat{\Omega}$) 500 times based on the estimated variance-covariance. For each draw, we calculate the metric of interest using the procedure discussed above and take the standard deviation of these predictions.

6. Results

The raw estimates from our model are contained in the supplementary appendix. To contextualize the results, we focus on the share of consumers that are predicted to purchase each cheese type.

6.1 Predicted market shares

Figure 2 holds the predicted market shares conditional on purchase. In Figure 2a animal-free dairy cheese is priced at £3.00 (per 200 g package), and in Figure 2b animal-free dairy cheese is priced at parity with premium dairy cheese (£2.42 per 200 g package). At our base prices (Figure 2a), the conditional market share of premium cheese is 27%. The conditional market shares of block, ball, and animal-free dairy cheese are 22% each. Nut-based cheese has the lowest conditional market share at 6%. When priced at parity with premium conventional cheese, the conditional market share of animal-free dairy increases by 11 percentage points to 33%, with most of this increase in market share coming at the expense of premium cheese.



(a) Animal-free dairy cheese (£3.00) (b) Animal-free dairy cheese (£2.42)

Figure 2. Predicted market shares (conditional on purchase). Standard errors are in parentheses. Based on the following prices (for 200 g packages): ball cheese (£1.77); block cheese (£2.09); premium cheese (£2.42); and nut-based cheese (£3.09).

The predicted market share of animal-free dairy cheese is considerably higher than the market share of cultivated meat predicted by studies in Canada (Slade, 2018b) and the US (Van Loo *et al.*, 2020). There are three notable differences between our analysis and these two previous studies. First, we examine consumers in the UK instead of North America. Preferences may differ between these regions, although Zollman-Thomas and Bryant (2021) find little difference in willingness to try animal-free dairy cheese in the US and the UK. Second, we examine preferences for animal-free dairy cheese as opposed to cultivated meat. As mentioned, animal-free dairy cheese may be more acceptable due to differences in production practices (i.e. cellular versus acellular methods) and because cheese is already considered a processed product. Third, our experiment was conducted in 2020, after the previous two experiments were completed. In the period between these studies, consumers may have become more comfortable with cellular agriculture or more motivated to reduce livestock production.

A critical question in the study of livestock substitutes is the extent to which these products reduce the consumption of livestock-derived products rather than being purchased by consumers who would otherwise have purchased a different plant-based product or would have opted against purchasing. To address this question, Figure 3 illustrates how the unconditional market shares for conventional dairy cheeses change when nut-based cheese and animal-free dairy cheese are introduced to the market. Note that these market shares differ from those in Figure 2 because they are not conditioned on purchasing a product (i.e. the probability of no purchase is included).

Introducing nut-based cheese to the market (without animal-free dairy cheese) reduces the collective market share of conventional cheeses by 6.9 percentage points. Conversely, it reduces the share of respondents who do not purchase any cheese by just 0.8 percentage points. More than half of the market share for nut-based cheese comes from consumers who would otherwise have purchased premium cheese.

The introduction of animal-free dairy cheese further reduces the share of conventional cheese by 14.0 percentage points. Over half of consumers who purchase animal-free dairy cheese would otherwise have consumed premium cheese, and another quarter would have consumed ball or block cheese. The remaining consumers would have purchased nut-based cheese (2.5 percentage points) or chosen the no purchase option (1.2 percentage points).

Our findings echo past research that has examined patterns of substitution between livestock products and plant-based alternatives, which has generally found that most of the demand for livestock alternatives comes at the expense of animal-derived products (Bryant, 2022; Slade, 2023; Slade and Markevych, 2023). One implication of these results is that the environmental impact of introducing animal-free dairy cheese depends primarily on the difference between the environmental footprints of animal-free dairy and conventional dairy rather than the relative footprints of animal-free dairy products and plant-based alternatives.

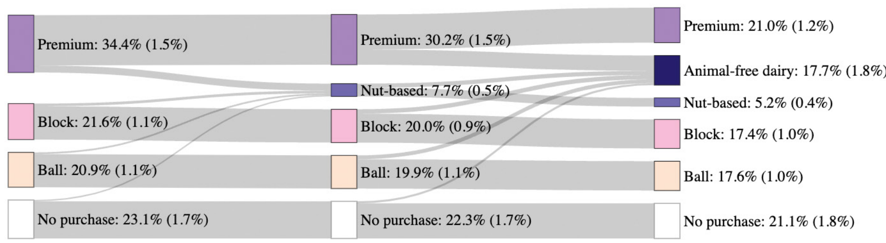


Figure 3. Unconditional market shares before and after the introduction of nut-based and animal-free dairy cheese. Standard errors are in parentheses. The left-hand of the diagram illustrates the predicted market shares without nut-based or animal-free dairy cheese. The middle panel of the diagram illustrates market shares when nut-based cheese is introduced. The right-hand side illustrates market shares when animal-free dairy cheese is introduced. Based on the following prices (for 200 g packages): ball cheese (£1.77); block cheese (£2.09); premium cheese (£2.42); nut-based cheese (£3.09); and animal-free dairy cheese (£3.00).

6.2 Market share elasticities and the price of animal-free dairy cheese

To further understand the relationship between conventional cheese, animal-free dairy cheese, and nut-based cheese, we calculate a set of market share elasticities, which are contained in Table 3. The own-price elasticities range from -1.32 to -2.36. Demand for basic cheeses (block and ball) is considerably more inelastic than demand for premium and vegan cheeses. Consistent with Figure 3, animal-free dairy cheese is more sensitive to changes in the price of premium cheese than to changes in the price of block or ball cheese. Similarly, premium and nut-based cheeses are more sensitive to changes in the price of animal-free dairy cheese than to changes in the prices of other products. These elasticities provide additional evidence that animal-free and nut-based cheeses are perceived as premium products.

As we discussed previously, there is considerable uncertainty about the price of animal-free dairy cheese. Figure 4 plots market shares across a range of prices for animal-free dairy cheese. Consistent with the high own-price elasticity in Table 3, the share of consumers who select animal-free dairy cheese ranges from 35% when animal-free dairy cheese is priced at £2.00 per 200 g package to 0.09% when it is priced at £7.00 per 200 g. At moderately high prices, animal-free dairy cheese would capture a niche market. For example, at £4.00 per 200 g package 7.5% of consumers would buy animal-free dairy. Although, at twice the price of premium cheese (£5.00 per 200 g package) only 2% of consumers would purchase animal-free dairy cheese. As expected, nut-based and premium cheese benefit the most from higher animal-free dairy cheese prices.

6.3 Diet and socio-demographic characteristics

As mentioned, our model contains diet and sociodemographic characteristics. These variables influence the utility that individuals derive from each type of cheese (according to Equation 1). In Table 4 we report the marginal effects of these covariates on the market shares of animal-free and nut-based cheese. The impact of these covariates on the market share for other cheese types is contained in the appendix, along with the raw estimates from the model.

Greater monthly cheese consumption is associated with a higher probability of purchasing both animal-free dairy and nut-based cheese. One potential explanation for this result is that those with high cheese consumption may be more worried about the ethical and environmental impact of their consumption decisions. Vegans, vegetarians, and flexitarians are considerably more likely to purchase nut-based cheese. However, these diets do not have a statistically significant impact on animal-free dairy cheese, suggesting that animal-free dairy cheese appeals as much to omnivores as it does to those who actively reduce their livestock consumption.

Table 3. Market share elasticities.

With respect to % change in the price of	% change in the market share of					
	Animal-free dairy	**Nut-based**	**Premium**	**Block**	**Ball**	**No purchase**
Animal-free dairy	−2.36 (0.184)***	0.928 (0.142)***	0.917 (0.080)***	0.380 (0.089)***	0.359 (0.036)***	0.163 (0.038)***
Nut-based	0.282 (0.036)***	−1.90 (0.173)***	0.090 (0.024)***	0.071 (0.019)***	0.044 (0.009)***	0.037 (0.006)***
Premium	0.880 (0.099)***	0.284 (0.069)***	−2.13 (0.200)***	0.440 (0.053)***	0.886 (0.068)***	0.153 (0.041)***
Block	0.263 (0.035)***	0.162 (0.036)***	0.317 (0.053)***	−1.32 (0.096)***	0.415 (0.077)***	0.148 (0.018)***
Ball	0.213 (0.028)***	0.085 (0.016)***	0.547 (0.055)***	0.356 (0.053)***	−1.43 (0.100)***	0.139 (0.018)***

Standard errors are in parentheses. *, **, *** denote statistical significance at the 10%, 5%, and 1% levels. Based on the following prices (for 200 g packages): ball cheese (£1.77); block cheese (£2.09); premium cheese (£2.42); nut-based cheese (£3.09), and animal-free cheese (£3.00).

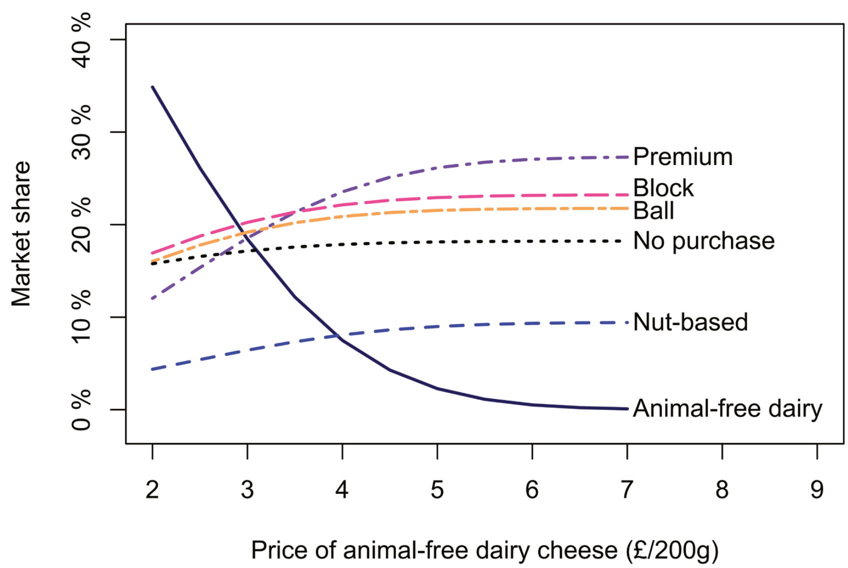


Figure 4. Predicted market shares as a function of the price of animal-free dairy cheese. Based on the following prices (per 200 g package): ball cheese (£1.77); block cheese (£2.09); premium cheese (£2.42); and nut-based cheese (£3.09).

Animal-free dairy cheese has a higher market share among those with higher incomes, rural residences, and liberal orientations. The coefficients on income and political orientation are consistent with past research examining demand for cultivated meat (Slade, 2018b); however, the coefficient on the urban index was unexpected. Nut-based cheese has a higher market share among individuals who are younger, more urban, and more liberal.

7. Welfare effects of higher cheese prices

Several commentators have suggested taxing livestock animal products in order to improve animal welfare and decrease greenhouse gas emissions. Initially, the idea of taxing livestock was mainly driven by animal

Table 4. Marginal effects of individual characteristics on market shares.

	Animal-free dairy	Nut-based
Diet		
Cheese consumption[a]	0.036 (0.006)***	0.008 (0.001)***
Vegan[b]	−0.001 (0.054)	0.618 (0.037)***
Vegetarian[b]	0.063 (0.039)	0.116 (0.025)***
Flexitarian[b]	0.045 (0.036)	0.078 (0.015)***
Sociodemographic		
Age	−0.003 (0.012)	−0.015 (0.006)**
Education	−0.005 (0.011)	−0.002 (0.003)
Female	−0.043 (0.035)	0.007 (0.008)
Income	0.033 (0.012)***	0.001 (0.003)
Urban index	−0.021 (0.010)**	0.009 (0.003)***
Liberal orientation	0.027 (0.014)*	0.009 (0.003)***

Standard errors are in parentheses. For continuous variables, the marginal effect is reported. For binary variables, the effect of a discrete change is reported. Standard errors are in parenthesis. *, **, *** denote statistical significance at the 10%, 5%, and 1% levels. Based on the following prices (per 200 g package): ball cheese (£1.77); block cheese (£2.09); premium cheese (£2.42); nut-based cheese (£3.09); and animal-free dairy cheese (£3.00).

[a] Number of times consumed per month.

[b] Relative to omnivore/other diet.

welfare concerns (Blackorby and Donaldson, 1992; Harvey and Hubbard, 2013; Lusk, 2011). Kuruc and McFadden (2021) estimate that the social cost of animal agriculture on animal welfare is much greater than its environmental cost, which suggests that a Pigouvian livestock tax is more justifiable on animal welfare grounds than on environmental grounds.

However, most of the recent interest in livestock taxes is rooted in concerns about GHG emissions. Although many countries place a price on GHG emissions, none have extended this price to cover emissions from livestock products (World Bank, 2022). One notable exception is the government of New Zealand, which recently announced its intention to tax emissions from farm animals (McKenzie, 2022). In the UK, large GHG emitters must purchase emission allowances on an emissions trading system. In 2022, the price of carbon in the UK's biweekly auctions averaged £70 per ton of CO_2 equivalent (CO_2e) (data available at https://www.theice.com/emissions/auctions/uk-emission-allowances).

The impact of extending carbon taxes to livestock emissions has been examined in a number of different studies (Bonnet *et al.*, 2018; Caillavet *et al.*, 2016; Slade, 2018a; Sall and Gren, 2015). In a survey of this literature, Bonnet *et al.* (2020) find that applying contemporaneous carbon prices to livestock products would reduce agricultural emissions by between 2–8%, depending on the level of taxation and the country being considered.

In this section, we simulate how higher prices for dairy cheese (such as those that might result from a livestock tax) would impact market shares and consumer welfare. As our survey only considers mozzarella cheese, we are not able to provide a complete analysis of how a livestock tax would impact overall cheese consumption. This tax would increase not only the price of mozzarella cheese but also the price of other cheeses and livestock products. However, Revoredo-Giha *et al.* (2018) estimate a low cross-price elasticity between cheese and other livestock products in the UK, and Bouhlal *et al.* (2013) find a similarly low elasticity between mozzarella and other cheeses in the US (we could not find a study of demand for cheese varieties within the UK). This suggests that our analysis may closely approximate the impact of livestock taxes on demand for mozzarella.

In our simulation, we examine price increases of between £0.05 and £0.25 per 200 g package, which are applied equally to all conventional dairy cheeses. For reference, a carbon price of £75 per ton of CO_2e (the average price in the UK in 2022) would correspond to an increase of £0.09 for a 200 g package of cheese, based on an emission factor of 6.135 kg of CO_2e per kg of cheese (the average of the two estimates for mozzarella cheese that are contained in Appendix A). We note that emissions from energy production, the primary source of emissions from animal-free dairy products, are already covered by the UK's carbon price.

We consider two different market scenarios: one in which animal-free dairy cheese is not available and another in which it is available. We calculate (unconditional) market shares using the same procedure that was used to generate Figures 2 and 3. The change in consumer welfare is calculated as the utility consumers receive from their most preferred option (see equation 1), divided by the estimated coefficient on price in our base model, which provides a money-metric utility measure. The results are contained in Table 5.

Across both scenarios, higher prices of dairy cheese result in lower market shares for dairy cheese and a decrease in consumer welfare. However, the presence of animal-free dairy cheese modifies both of these results. The reduction in the market share of dairy cheese is 80% greater when animal-free dairy cheese is available, as consumers are more willing to give up conventional cheese if they can switch to a close substitute. Furthermore, the change in consumer welfare is approximately 20% lower when animal-free dairy cheese is available. There are two reasons for the moderation in consumer harm. First, consumers who purchase animal-free dairy cheese at the base prices are not affected by an increase in the conventional cheese price. Second, some consumers who purchase conventional cheese at the base prices would switch to animal-free dairy cheese when prices increase. This implies that their welfare loss is less than the price increase (if it were not, then they would purchase the conventional cheese despite the price increase).

The simulation results suggest that the presence of animal-free dairy cheese could make livestock taxes more effective and less socially costly. However, the results in Table 5 can be viewed from another angle. Without animal-free dairy cheese, dairy prices would need to increase by over £0.25 per 200 g to achieve a 2.36 percentage point reduction in the share of consumers who purchase dairy cheese. If taxes are based on GHG emissions, such a price increase would be equivalent to a carbon price of £200 per ton of CO_2e (based on an emissions factor of 6.135 kg of CO_2e per kg of cheese). Furthermore, this estimate is likely an upper bound on the true impact of carbon prices, as we do not account for the impact of carbon prices on the price of substitute goods. In contrast, the introduction of animal-free dairy cheese reduces the conditional market share of dairy cheese by 14 percentage points (see Figure 3), without any change in the price of dairy cheese.

Table 5. Effect of increased dairy cheese prices

Change in dairy cheese price (per 200 g)	**Without animal-free dairy cheese**		**With animal-free dairy cheese**	
	Change in dairy cheese share (pp)[a]	**Change in consumer welfare[b]**	**Change in dairy cheese share (pp)[a]**	**Change in consumer welfare[b]**
£0.05	−0.462	−£0.037	−0.839	−£0.030
£0.10	−0.930	−£0.074	−1.68	−£0.059
£0.15	−1.40	−£0.110	−2.53	−£0.088
£0.20	−1.88	−£0.146	−3.39	−£0.116
£0.25	−2.36	−£0.182	−4.25	−£0.144

The predictions in the table use the following base prices (for 200 g packages): ball cheese (£1.77); block cheese (£2.09); premium cheese (£2.42); nut-based cheese (£3.09); and animal-free dairy cheese (£3.00).

[a] Percentage point (pp) change in the unconditional market share of premium, block, and ball cheese.

[b] The change in the utility an individual receives from their most preferred option, divided by the coefficient on price.

8. Conclusion

In this paper, we examine consumer demand for animal-free dairy cheese in the UK using a hypothetical discrete choice experiment. Our primary finding is that a significant minority of consumers are willing to adopt animal-free dairy cheese if it is priced competitively with conventional dairy cheese: animal-free dairy has a conditional market share of 22% when priced at a 25% markup relative to premium dairy cheese. When animal-free dairy cheese is priced at parity with premium dairy cheese, this market share increases to 33%. However, most consumers are unwilling to pay a substantial premium for animal-free dairy cheese, with market shares falling to 2% when the price of animal-free dairy cheese is twice the price of premium dairy cheese. These predicted market shares demonstrate that a viable market exists for animal-free dairy cheese if the industry is able to create a product that is competitive with conventional dairy cheese in terms of both taste and price.

Our research also speaks to the common suspicion that demand for alternative proteins comes at the expense of other plant-based products. In fact, three-quarters of those who buy animal-free dairy cheese would have purchased conventional cheese if animal-free dairy was unavailable. Notably, most of the market share for animal-free dairy cheese comes at the expense of premium cheese. The potential loss in market share from animal-free dairy cheese is a significant threat to the UK dairy industry. To better compete with animal-free dairy cheese, the dairy industry might consider marketing products with enhanced animal welfare and environmental attributes, two of the major selling points for animal-free dairy cheese.

We also find that the two types of non-animal cheese (animal-free dairy and nut-based cheese) are imperfect substitutes. Although the introduction of animal-free dairy cheese reduces the market share of nut-based cheese, both products maintain a viable market share across all our pricing scenarios — albeit nut-based cheese has less than 1/3 of the market share of animal-free dairy cheese at our base prices. These market shares suggest that animal-free and nut-based cheese appeal to somewhat different sets of consumers and can co-exist in the same market. Taste has previously been identified as one of the barriers to the adoption of nut-based cheese and may explain the substantially higher market share for animal-free dairy cheese.

From the perspective of public policy, the availability of animal-free dairy products attenuates the welfare losses from increased dairy cheese prices, which could make it more politically palatable to enact a tax on livestock products. However, higher prices have a relatively muted impact on market shares for livestock products compared to the impact of introducing animal-free dairy cheese. Our findings suggest that continued public investment in the development of livestock alternatives and a hospitable regulatory environment may be more effective in reducing livestock emissions than a tax on livestock products.

To our knowledge, we have provided the first estimates of the potential market share for animal-free dairy cheese. As such, there is considerable scope for future work in this area. Given that our primary goal in this paper was to understand the potential market share for animal-free dairy cheese, we did not examine consumers' motivations for choosing animal-free dairy products. Future work is needed to uncover these underlying determinants of demand, which might include dietary restrictions (e.g., lactose intolerance) and concerns for animal welfare and the environment. Conversely, food neophobia may inhibit consumption of animal-free dairy products.

Adoption of animal-free dairy cheese might also depend on product characteristics that are omitted from our experiment. For example, consumers may feel more comfortable purchasing a novel product if it is marketed by a known brand. Conversely, conventional dairy producers may be able to cut into the market share of animal-free dairy products through product labelling that highlights enhanced attributes in dairy products (e.g. organic certification or place-based labelling).

Our analysis is also limited in geographic and product space; we only consider the market for mozzarella cheese in the UK. Animal-free dairy is currently marketed in limited quantities in ice cream, spreadable cheeses, and beverages. It would be interesting to explore how consumer preferences vary across these product categories. Additionally, dairy products have various cultural and culinary functions across different countries. Further research is needed to better understand the potential for animal-free dairy to be adopted in these distinct consumption contexts.

The predicted market shares in this paper are generated through a hypothetical experiment, as animal-free dairy cheese is not yet available for purchase. Although consumers were asked to make decisions as they would in an actual purchase context, such experiments are subject to hypothetical biases (Louviere *et al.*, 2000). Furthermore, our experimental instructions may be an imperfect replacement for the sensory experience of consuming the product; while respondents were told that animal-free dairy cheese would taste the same as conventional dairy cheese, some individuals may have harbored doubts about the sensory appeal of the product. Our results should be re-examined using non-hypothetical experiments and sales data when animal-free dairy cheese is available for purchase.

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References

ADM. 2022. *ADM and New Culture announce strategic partnership to scale up alter- native dairy products*. Available online at https://www.adm.com/en-us/news/news-releases/2022/8/adm-and-new-culture-announce-strategic-partnership-to-scale-up-alternative-dairy-products/

Aguirre-Villegas, H., S. Kraatz, F. Milani, A. Newenhouse, T. Passos-Fonseca and D. Reinemann. 2011. *Sustainable Cheese Production: Understand the Carbon Footprint of Cheese*. University of Wisconsin-Extension, Cooperative Extension 28. University of Wisconsin, Madison, WI.

Alae-Carew, C., R. Green, C. Stewart, B. Cook, A.D. Dangour and P.F. Scheelbeek. 2022. The role of plant-based alternative foods in sustainable and healthy food systems: Consumption trends in the UK. *Science of The Total Environment* 807(3): 151041. https://doi.org/10.1016/j.scitotenv.2021.151041

Behm, K., M. Nappa, N. Aro, A. Welman, S. Ledgard, M. Suomalainen and J. Hill. (2022). Comparison of carbon footprint and water scarcity footprint of milk protein produced by cellular agriculture and the dairy industry. *The International Journal of Life Cycle Assessment* 27(8): 1017–1034.

Berlin, J. 2002. Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. *International Dairy Journal* 12(11): 939–953. https://doi.org/10.1016/S0958-6946(02)00112-7

Blackorby, C. and D. Donaldson 1992. Pigs and guinea pigs: a note on the ethics of animal exploitation. *The Economic Journal* 102(415): 1345–1369. https://doi.org/10.2307/2234794

Berners-Lee, M., C. Hoolohan, H. Cammack and C. Hewitt. 2012. The relative greenhouse gas impacts of realistic dietary choices. *Energy Policy* 43: 184–190. https://doi.org/10.1016/j.enpol.2011.12.054

Bonnet, C., Z. Bouamra-Mechemache and T. Corre. 2018. An environmental tax towards more sustainable food: empirical evidence of the consumption of animal products in France. *Ecological Economics* 147: 48–61. https://doi.org/10.1016/j.ecolecon.2017.12.032

Bonnet, C., Z. Bouamra-Mechemache, V. Réquillart and N. Treich. 2020. Regulating meat consumption to improve health, the environment and animal welfare. *Food Policy* 97: 101847. https://doi.org/10.1016/j.foodpol.2020.101847

Bouhlal, Y., O. Capps Jr and A. Ishdorj. 2013. *Estimating the censored demand for US cheese varieties using panel data: Impact of economic and demographic factors*. Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2013 AAEA & CAES Joint Annual Meeting, Washington, DC, August 4–6, 2013.

Bryant, C. and J. Barnett. 2020. Consumer acceptance of cultured meat: An updated review (2018–2020). *Applied Sciences* 10(15): 5201. https://doi.org/10.3390/app10155201

Bryant, C. and C. Dillard. 2019. The impact of framing on acceptance of cultured meat. *Frontiers in Nutrition* 6: 103. https://doi.org/10.3389/fnut.2019.00103

Bryant, C., K. Szejda, N. Parekh, V. Deshpande and B. Tse. 2019. A survey of consumer perceptions of plant-based and clean meat in the USA, India, and China. *Frontiers in Sustainable Food Systems* 3: 11. https://doi.org/10.3389/fsufs.2019.00011

Bryant, C.J. 2022. Plant-Based Animal Product Alternatives Are Healthier and More Environmentally Sustainable than Animal Products. *Future Foods* 6: 100174. https://doi.org/10.1016/j.fufo.2022.100174

Bureau of Labour Statistics. 2021. *Consumer Expenditure Survey*. Available online at https://www.bls.gov/cex/.

Caillavet, F., A. Fadhuile and V. Nichele. 2016. Taxing animal-based foods for sustainability: environmental, nutritional and social perspectives in France. *European Review of Agricultural Economics* 43(4): 537–560. https://doi.org/10.1093/erae/jbv041

Dalla Riva, A., J. Burek, D. Kim, G. Thoma, M. Cassandro and M. De Marchi. 2017. Environmental life cycle assessment of Italian mozzarella cheese: Hotspots and improvement opportunities. *Journal of Dairy Science* 100(10): 7933–7952. https://doi.org/10.3168/jds.2016-12396

Department for Business, Energy and Industrial Strategy. 2020. *2018 UK Greenhouse Gas Emissions, Final figures*. Available online at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/862887/2018_Final_greenhouse_gas_emissions_statistical_release.pdf.

Department for Environment, Food and Rural Affairs. 2021. *Agri-climate report 2021*. Available online at https://www.gov.uk/government/statistics/agri-climate-report-2021/agri-climate-report-2021.

Department for Environment, Food and Rural Affairs. 2022. *Livestock numbers in England and the UK*. Available online at https://www.gov.uk/government/statistical-data-sets/.

Elzerman, J.E., A.C. Hoek, M.A. van Boekel and P.A. Luning. 2011. Consumer acceptance and appropriateness of meat substitutes in a meal context. *Food Quality and Preference* 22(3): 233–240. https://doi.org/10.1016/j.foodqual.2010.10.006

Elzerman, J.E., A.C. Hoek, M.J. van Boekel and P.A. Luning. 2015. Appropriateness, acceptance and sensory preferences based on visual information: A web-based survey on meat substitutes in a meal context. *Food Quality and Preference* 42: 56–65. https://doi.org/10.1016/j.foodqual.2015.01.010

Finnegan, W., J. Goggins, E. Clifford and X. Zhan. 2017. Global warming potential associated with dairy products in the Republic of Ireland. *Journal of Cleaner Production* 163: 262–273. https://doi.org/10.1016/j.jclepro.2015.08.025

Flysjö, A., M. Thrane and J.E. Hermansen. 2014. Method to assess the carbon footprint at product level in the dairy industry. *International Dairy Journal* 34(1): 86–92. https://doi.org/10.1016/j.idairyj.2013.07.016

Food and Agricultural Organization. 2021. *FAOSTAT*. Available online at https://www.fao.org/faostat/.

Gatten, E. 2021. Meat taxes will make British farmers go greener, says George Eustice. *The Telegraph*. Available online at https://www.telegraph.co.uk/environment/2021/10/29/meat-taxes-will-make-british-farmers-go-greener-says-george/.

Gerber, P.J., H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, G. Tempio, *et al.* 2013. *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations, Rome.

Good Food Institute. 2021. *Plant-based food retail sales reach $7 billion*. Available online at https://gfi.org/blog/spins-data-release-2021/

Government of the United Kingdom. 2021. *Net Zero Strategy: Build Back Greener*. Available online at https://www.gov.uk/government/statistics/agri-climate-report-2021/agri-climate-report-2021.

Graça, J., A. Oliveira and M.M. Calheiros. 2015. Meat, beyond the plate. Data-driven hypotheses for understanding consumer willingness to adopt a more plant-based diet. *Appetite* 90: 80–90. https://doi.org/10.1016/j.appet.2015.02.037

Grossmann, L. and D.J. McClements. 2021. The science of plant-based foods: Approaches to create nutritious and sustainable plant-based cheese analogs. *Trends in Food Science & Technology* 118: 207–229. https://doi.org/10.1016/j.tifs.2021.10.004

Hamdan, I. and J. Senez. 1992. The economic viability of single cell protein (SCP) production in the twenty-first century. In E. DaSilva, C. Ratledge & A. Sasson (Eds.), Biotechnology*: Economic and social aspects: Issues for developing countries*. Cambridge University Press, Cambridge, pp. 142–164.

Harvey, D. and C. Hubbard. 2013. Reconsidering the political economy of farm animal welfare: An anatomy of market failure. *Food Policy* 38: 105–114. https://doi.org/10.1016/j.foodpol.2012.11.006
Hess, S. and D. Palma. 2019. Apollo: a flexible, powerful and customisable freeware package for choice model estimation and application. *Journal of Choice Modelling* 32: 100170. https://doi.org/10.1016/j.jocm.2019.100170
Hoek, A.C., P.A. Luning, A. Stafleu and C. de Graaf. 2004. Food-related lifestyle and health attitudes of Dutch vegetarians, non-vegetarian consumers of meat substitutes, and meat consumers. *Appetite* 42(3): 265–272. https://doi.org/10.1016/j.appet.2003.12.003
Islam, T., J.J. Louviere and P.F. Burke. 2007. Modeling the effects of including/excluding attributes in choice experiments on systematic and random components. International *Journal of Research in Marketing* 24(4): 289–300. https://doi.org/10.1016/j.ijresmar.2007.04.002
Järviö, N., N.L. Maljanen, Y. Kobayashi, T. Ryynänen and H. Tuomisto. 2021. An attributional life cycle assessment of microbial protein production: A case study on using hydrogen-oxidizing bacteria. *Science of the Total Environment* 776: 145764. https://doi.org/10.1016/j.scitotenv.2021.145764
Kardes, F. R., S.S. Posavac and M.L. Cronley. 2004. Consumer inference: A review of processes, bases, and judgment contexts. *Journal of Consumer Psychology* 14(3): 230–256. https://doi.org/10.1207/s15327663jcp1403_6
Keerie, M. 2021. *Record $3.1 billion invested in alt proteins in 2020 signals growing market momentum for sustainable proteins*. Available online at https://gfi.org/blog/2020-state-of-the-industry-highlights/.
Kim, D., G. Thoma, D. Nutter, F. Milani, R. Ulrich and G. Norris. 2013. Life cycle assessment of cheese and whey production in the USA. *The International Journal of Life Cycle Assessment* 18(5): 1019–1035. https://doi.org/10.1007/s11367-013-0553-9
Kuruc, K. and J. McFadden. 2021. *Monetizing the Externalities of Animal Agriculture: Insights from an Inclusive Welfare Function*. Working Paper, University of Oklahoma. University of Oklahoma, Norman, OK.
Linder, T. 2019. Making the case for edible microorganisms as an integral part of a more sustainable and resilient food production system. *Food Security* 11(2): 265–278. https://doi.org/10.1007/s12571-019-00912-3
Louviere, J.J., D.A. Hensher and J.D. Swait. 2000. *Stated choice methods: analysis and applications*. Cambridge University Press, Cambridge.
Lusk, J.L. (2011). The market for animal welfare. *Agriculture and Human Values* 28: 561–575. https://doi.org/10.1007/s10460-011-9318-x
Malek, L., W.J. Umberger and E. Goddard. 2019. Committed vs. uncommitted meat eaters: Understanding willingness to change protein consumption. *Appetite* 138: 115–126. https://doi.org/10.1016/j.appet.2019.03.024
Mancini, M.C. and F. Antonioli. 2019. Exploring consumers' attitude towards cultured meat in Italy. *Meat Science* 150: 101–110. https://doi.org/10.1016/j.meatsci.2018.12.014
McKenzie, P. 2022. New Zealand farmers propose paying for emissions to tackle climate change. *The Guardian*. Available online at https://www.theguardian.com/world/2022/jun/08/new-zealand-farmers-propose-paying-for-emissions-to-tackle-climate-change.
Michel, F., C. Hartmann and M. Siegrist. 2021. Consumers' associations, perceptions and acceptance of meat and plant-based meat alternatives. *Food Quality and Preference* 87: 104063. https://doi.org/10.1016/j.foodqual.2020.104063
Modern Kitchen. 2021. *Products*. Available online at https://eatmodern.kitchen/products.
Morach, B., B. Witte, D. Walker, E. von Koeller, F. Grosse-Holz, J. Rogg, M. Brigl, N. Dehnert, P. Obloj, S. Koktenturk and U. Schulze. 2021. *Food for Thought: The Protein Transformation*. Available online at https://www.bcg.com/publications/2021/the-benefits-of-plant-based-meats
Perfect Day. 2021. *Comparative GHG emissions assessment of Perfect Day whey protein to dairy protein*. Available online at https://resources.perfectdayfoods.com/articles/lca-executive-summary.
Perfect Day. 2022. *Perfect Day*. Available online at https://perfectday.com/find-us/.
Quantis. 2022. *Violife 100% vegan alternative to cheese vs. dairy cheese in Europe, UK, US and Canada*. Available online at https://violifefoods.com/wp-content/uploads/2021/12/Violife_TechnicalSummary_2021-12-20-FINAL.pdf

Revoredo-Giha, C., N. Chalmers and F. Akaichi. 2018. Simulating the impact of carbon taxes on greenhouse gas emission and nutrition in the UK. *Sustainability* 10(1): 134. https://doi.org/10.3390/su10010134

Ritchie, H. and M. Roser. 2013. Land Use. *Our World in Data*. Available online at https://ourworldindata.org/land-use.

Sall, S. and M. Gren. 2015. Effects of an environmental tax on meat and dairy consumption in Sweden. *Food Policy* 55: 41–53. https://doi.org/10.1016/j.foodpol.2015.05.008

Schösler, H., J. de Boer and J.J. Boersema. 2012. Can we cut out the meat of the dish? Constructing consumer-oriented pathways towards meat substitution. *Appetite* 58(1): 39–47. https://doi.org/10.1016/j.appet.2011.09.009

Shankleman, J. 2021. BOE's Breeden Says Banks Unprepared for $150 Carbon Price. *Bloomberg*. Available online at https://www.bloomberg.com/news/articles/2021-05-18/boe-s-breeden-says-banks-are-unprepared-for-150-carbon-price.

Short, E.C., A.J. Kinchla and A.A. Nolden. 2021. Plant-Based Cheeses: A Systematic Review of Sensory Evaluation Studies and Strategies to Increase Consumer Acceptance. *Foods* 10(4): 725. https://doi.org/10.3390/foods10040725

Siegrist, M. and C. Hartmann. 2019. Impact of sustainability perception on consumption of organic meat and meat substitutes. *Appetite* 132: 196–202. https://doi.org/10.1016/j.appet.2018.09.016

Slade, P. 2018a. The effects of pricing Canadian livestock emissions. *Canadian Journal of Agricultural Economics* 66(2): 305–329. https://doi.org/10.1111/cjag.12157

Slade, P. 2018b. If you build it, will they eat it? Consumer preferences for plant-based and cultured meat burgers. *Appetite* 125: 428–437. https://doi.org/10.1016/j.appet.2018.02.030

Slade, P. 2023. Does plant-based milk reduce sales of dairy milk? Evidence from the almond milk craze. *Agricultural and Resource Economics Review* 52(1): 112–131. https://doi.org/10.1017/age.2022.22

Slade, P. and M. Markevych. 2023. Killing the sacred dairy cow? Consumer preferences for plant-based milk alternatives. *Agribusiness*, in press.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel and C. de Haan. 2006. *Livestock's long shadow: environmental issues and options*. Food & Agriculture Organization, Rome.

Tuomisto, H. L. 2022. Challenges of assessing the environmental sustainability of cellular agriculture. *Nature Food*, 3: 801–803.

Valente, J.d.P.S., R.A. Fiedler, M. Sucha Heidemann and C.F.M. Molento. 2019. First glimpse on attitudes of highly educated consumers towards cell-based meat and related issues in Brazil. *PLOS ONE* 14(8): e0221129. https://doi.org/10.1371/journal.pone.0221129

Van Loo, E.J., V. Caputo and J.L. Lusk. 2020. Consumer preferences for farm-raised meat, lab-grown meat and plant-based meat alternatives: Does information or brand matter? *Food Policy* 95: 101931. https://doi.org/10.1016/j.foodpol.2020.101931

Van Middelaar, C., P. Berentsen, M. Dolman and I. De Boer. 2011. Eco-efficiency in the production chain of Dutch semi-hard cheese. *Livestock Science* 139(1–2): 91–99. https://doi.org/10.1038/s43016-022-00616-6

Weinrich, R., M. Strack and F. Neugebauer. 2020. Consumer acceptance of cultured meat in Germany. *Meat Science* 162: 107924. https://doi.org/10.1016/j.livsci.2011.03.013

Wilks, M. and C.J. Phillips. 2017. Attitudes to in vitro meat: A survey of potential consumers in the United States. *PLOS ONE* 12(2): e0171904. https://doi.org/10.1371/journal.pone.0171904

World Bank. 2022. *Carbon Pricing Dashboard*. Available online at https://carbonpricingdashboard.worldbank.org/

Zollman-Thomas, O. and C. Bryant. 2021. Don't have a cow, man: Consumer acceptance of animal-free dairy products in five countries. *Frontiers in Sustainable Food Systems* 5: 223. https://doi.org/10.3389/fsufs.2021.678491

Appendix A
Overview of emissions factors from cheese production

Table A1. Emission factors for cheese

Study	Country and product	Emissions factor[a]	
		On-farm	Total
Berlin (2002)	Semi-hard cheese in Sweden	8.30	8.69
Berners-Lee *et al.* (2012)	Cheese in the United Kingdom	12.12	12.35
Dalla Riva *et al.* (2017)	High-moisture mozzarella in Italy	5.54	6.27
Finnegan *et al.* (2017)	Cheese in Ireland	4.68	5.90
Flysjo *et al.* (2014)	Cheese in Denmark	6.00	6.50
Kim *et al.* (2013)	Mozzarella in United States	6.71	7.28
Van Middelaar *et al.* (2011)	Semi-hard cheese in the Netherlands	7.50	8.47

[a] kg of CO_2e per kg of retail product. Does not include emissions past the processor (i.e. retailing and home consumption).

Appendix B
Information provided to survey respondents

Participants were provided the following information about the production method and taste of animal-free dairy cheese:

Legendairy foods is launching a new mozzarella product, made without any animals involved. Instead of relying on cows for milk, Legendairy uses a process similar to that of beer or soy-sauce production where microorganisms produce the ingredients. The main ingredients of traditional cheese are the proteins whey and casein — these are what the microorganism makes. To begin this process, the part of cow DNA that makes milk proteins is copied and inserted into the microorganisms' genes. Through fermentation, these microorganisms start to produce proteins, just the same as the proteins a cow would make. These proteins are collected from the microorganisms and turned into products such as mozzarella. Legendairy mozzarella production doesn't involve any animals (nor the antibiotics that animals are often fed), doesn't contain lactose, has a much lower carbon footprint than regular cheese and it tastes and behaves exactly the same as regular mozzarella.