Report E019R01

EXPLORING THE IMPACT OF PLANT-BASED MILK ALTERNATIVES IN THE US

Preregistration for an observational study

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EXECUTIVE SUMMARY

We provide a detailed research plan to evaluate the impact of the increasing availability of plant-based milk alternatives on demand for dairy fluid milk products in the United States. We will investigate this question by conducting three analyses: (1) gathering and comparing different sources of grocery sales data to investigate data variability and to determine whether plant-based sales are sufficient to replace declining dairy sales, (2) summarizing research on the relationship between plant-based and dairy milks to determine whether the products are price substitutes for each other, and (3) estimating demand for dairy milk in separate periods between 2001-2019 and comparing each period's responsiveness to price fluctuations to determine whether dairy milk demand has undergone major changes that could have been caused by the expansion of plant-based milk products.

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1. INTRODUCTION

Plant-based alternatives to animal food products are making headlines, and dairy alternatives in particular have expanded in variety and market presence in the past decade. Some advocates hypothesize that the increasing abundance of plant-based versions of fluid milk, butter, cheese, and yogurt has offset demand for dairy products by providing competitive alternatives, while some in the industry suggest otherwise. However, empirical evidence about the impact of growth in availability of and demand for plant-based alternatives on demand for animal products is limited.

This preregistration provides a detailed research plan to evaluate the impact of plant-based milk alternatives, specifically their increasing availability, on demand for dairy fluid milk products in the United States (US). Informed by historical data, previous research, and economic theory, we will examine three relationships to investigate the impact of plant-based milks by evaluating: (1) whether sales of plant-based alternatives are sufficient to replace declining dairy sales, (2) whether cross-price elasticities indicate substitution, and (3) whether the own-price elasticity of dairy products has increased over time, suggesting an increase in the presence of substitute products.

Our work expands on the literature around milk consumption and substitution patterns that has recently begun to include plant-based alternatives. Most closely related to our first line of evidence is Stewart et al [1], which applies a vector autoregressive (VAR) time-series model to grocery scanner data to show that the change in growth rate

of plant-based milk quantity sales can explain about 1/5th of the decrease in quantity sales of dairy milk. The authors use the results of the VAR model to simulate counterfactuals in which plant-based sales grow at a much slower rate, a phenomenon that the authors suggest might have occurred if the government had enacted a policy preventing companies from selling plant-based alternative products with the word “milk” on their labels. As expected, the research design does not provide causal identification but does find correlational evidence suggesting that sales of plant-based milks cause some decline in dairy milk sales. However, our previous work on plant-based meats suggests there may be as-yet-unexplained variance between different sources of grocery scanner data. We will collect data on plant-based milk prices, quantity sales, and dollar sales from public sources in order to validate the IRI data used in Stewart et al’s analysis.

A small body of literature investigates the relationships between types of plant-based milks and dairy milks by estimating cross-price elasticity, or how the quantity demanded of one product responds to changes in price of another. Dhar and Foltz [2] shows that early commercial soy milk products were substitutes only for flavored dairy milks. Using more current data, Dharmasena and Capps [3] shows that soy milk is a substitute for plain dairy milk averaged across all types. Copeland and Dharmasena [4] finds a similar relationship for soy and dairy milk, although the estimates of cross-price elasticities between almond and dairy milks suggest a complement relationship. Li [5] finds that coconut, almond, and soy milks are complements for plain dairy milk. Ghazaryan [6] finds that soy, almond, and “all other” nondairy milks are substitutes for skim dairy milk; almond and soy milks are complements for 2% and 1% dairy milk combined; and almond milk is a substitute for whole dairy milk while soy milk is a complement. We will qualitatively synthesize these results to compile and clarify these relationships.

These studies provide evidence of observable price relationships between plant-based and dairy milk as well as an indication that increasing plant-based milk sales can predict some of the decrease in dairy milk sales. However, there is also evidence that relative milk prices were fairly stable during the study periods [1], which indicates that plant-based and dairy milks may be imperfect substitutes for each other. In other words, relative prices may not be the only influence that plant-based milks have on the demand for dairy milk. Indeed, economic theory suggests

that demand for plain dairy milk should be determined by several factors, including dairy milk prices; the prices and availability of substitute products like nondairy milk and other ready-to-drink beverages; consumer incomes; expectations about future prices; and tastes and preferences. Theory also suggests that the own-price elasticity of demand for any product, a measure of the responsiveness of demand to price changes that is calculated from the underlying demand structure, will increase in the long run when there are more substitute products available. We will therefore look for evidence of changes to the structure of dairy milk demand that could have been caused by the increase in the number and variety of plant-based milks; we will do so by estimating and comparing short-run plain dairy milk price elasticities across different time periods. Our investigation will employ methods used in the energy economics literature to investigate potential structural changes in demand for fuel [7; 8]. While the available data do not allow us to isolate the different reasons for substitution, evidence of an increase in the own-price elasticity of dairy milk over time would provide support for the existence of a substitution relationship between the availability of plant-based milk and demand for dairy milk based on other factors besides price.

2. VALIDATING GROCERY DATA

Much of the revealed preference¹ research on purchasing behavior and price elasticities relies on grocery scanner or consumer panel data covering sales quantities, prices, and characteristics of individual products. Marketing firms like Nielsen, IRI, and SPINS collect these data directly from food retailers and consumers. While these data sets offer a high level of quality and detail, our previous work suggests there is some unexplained variance in publicly reported figures produced by these firms.

To better understand this variability and to validate the data used in [1], we will compare public data on plant-based milk sales with the data extracted from the paper. First, we will search government and industry publications for annual country-level US data on three measures of the plant-based milk alternative market: average unit prices, quantity sales, and dollar sales (where dollar sales = average unit price $\times$ quantity sales). Second, we will extract

the data. When two of the three measures are available and comparable from a single data source, we will calculate the third measure. For example, if a source provides dollar sales and quantity sales for a given year, we will calculate average price. Third, the data will be coded by source (for example: IRI, Nielsen, or SPINS). We have collected several publications and extracted their data as described above for our previous work, but we have not yet analyzed these data. Fourth, we will use data extraction software to recover the quantity sales data published in the figures of Stewart et al, and calculate the 52-week rolling sums for comparison with the publicly available data. Finally, for both the dollar and quantity sales data, we will compare the various estimates to look for consistency between sources. If possible, we will compare average prices over time to validate the observation in Stewart et al that plant-based milks experienced no major changes in price from 2013 to 2017.

3. SYNTHESIS OF ELASTICITIES

Our qualitative synthesis of cross-price elasticity estimates will follow the synthesis without meta-analysis (SWiM) reporting guidelines [9; 10]. SWiM guidelines ensure transparent and systematic reporting of synthesis methods when meta-analysis is not applied. Campbell et al [9] provide a list of nine items that contain guidelines for reporting methods in both the preregistration stage and the publication stage of a project conducting qualitative synthesis of quantitative results. We discuss our synthesis methodology using a consolidated version of these guidelines as a framework.

3.1. Study selection and grouping criteria

Our main criterion for selecting studies is the presence of an empirically estimated cross-price elasticity of demand between plant-based and dairy milks. We have previously conducted a literature search using the key words “estimated,” “cross-price elasticity,” “milk demand,” “dairy,” “nondairy,” “soy milk,” “almond milk,” “oat milk,” and “plant-based milk,” and we identified the five studies described in Section 1. We have read these papers for a high-level understanding of the research designs and conclusions, but we have not extracted or analyzed information from these studies. The research designs of the identified studies are broadly similar: all use data on individual purchases to estimate demand systems that are similar in concept but differ in specification details. These studies typi-

¹ Revealed preference studies examine consumer behavior by analyzing data on their observed market choices. This stands in contrast to stated preference research, which uses surveys or choice experiments to gather data on hypothetical behavior.

cally report elasticity estimates for several pairs of products, and we will group the results accordingly. For example, we will group estimates of the elasticity of soy milk demand with respect to a change in whole dairy milk price distinctly from estimates of elasticities of whole dairy demand with respect to almond milk price.

3.2. Standardized metric

Cross-price elasticity of demand is, by definition, constructed to be a unit-free measurement of the percentage change in quantity demanded of one good that is associated with a one percent increase in the price of another good. Therefore, elasticities are already standardized across studies. We will use elasticity magnitude and sign as our standardized metric for this synthesis. The sign of a cross-price elasticity estimate has economic significance, indicating whether a pair of products behave as substitutes (+) or complements (-); similarly, the magnitude of the elasticity provides information on the strength of the relationship. While the estimate itself is standardized, differences in empirical setting and research methodology between studies will affect the magnitude and sign of the estimate.

3.3. Synthesis method

From each study and for each estimate of cross-price elasticity within the study, we will extract the data source, sample size, sample period, estimation strategy, point estimate, confidence interval (CI), and *p* value. We will then calculate summary statistics of the available estimated elasticities, namely the mean of the elasticity point estimates and number of estimates. We will use vote counting, or tallying the number of positive and negative estimates, to qualitatively discuss the research consensus on whether two goods are complements or substitutes. We will construct forest plots for each elasticity using point estimates, CIs, the mean of point estimates, and the effect threshold of zero,² and we will analyze the magnitude of the mean of point estimate elasticities.

3.4. Discussion of synthesis conclusions

Briefly, we will qualitatively discuss differences in the reported effects between studies in the context of data sources, sample size, empirical setting (sample period or geography), estimation strategy, CIs, and *p* values of results. We will also briefly and qualitatively discuss the certainty of our

synthesis conclusions by considering the residual risk of bias for each study and visually examining the similarities between estimates from different studies using the forest plots. In our final publication for this project, we will summarize the results and discuss the conclusions of our synthesis, clearly listing which studies contributed to our conclusions.

4. DAIRY ELASTICITY ESTIMATION MODEL

Our final analysis will look for evidence of an increase in the own-price elasticity of plain dairy milk demand over time. As discussed in Section 1, economic theory suggests that the underlying structure of demand for plain dairy milk is determined by several factors. Theory also leads us to expect that demand for dairy milk will become more responsive to changes in its own price, since an increase in the number and availability of substitute products should change the structure of demand by altering consumer behavior in the long run. While we cannot presently use causal inference to isolate the effect of increasing availability of plant-based alternatives on dairy milk demand, the observation of these changes in dairy milk price elasticity would provide support that this causal relationship could exist as well as give important insight in the changing nature of dairy milk demand.

4.1. Demand model and specification

To test whether own-price elasticity of plain dairy milk has changed over time, we will recover and compare price elasticities estimated for separate time blocks using monthly data from 2001-2019. We will use an almost ideal demand system (AIDS) model, which has desirable theoretical and statistical properties that make it a common choice in the extensive body of research on dairy milk demand [11]. Combining this model with a consistent data set will allow us to compare our estimated elasticities with each other and against results from previous studies.

Our model will estimate the parameters in a system of three demand equations: demand for plain dairy milk, for other nonalcoholic beverages, and for all *other* foods and beverages excluding products in the former two categories. Plain dairy milk will include unflavored whole, 2%, 1%, and skim dairy milks. Other nonalcoholic beverages will include bottled water, juice, and other beverages except

² We choose zero as the effect threshold since our economic conclusions about the elasticity relationship change on either side of this threshold.

plant-based milks.³ The demand estimation procedure will regress the monthly budget expenditure share of a product category on prices of all other categories (in logarithmic form); the logarithm of the ratio of total expenditure and a constructed price index; a category-specific intercept; and a category-time specific error term. The AIDS model is derived under the assumption that expenditure shares sum to one, the so-called “adding-up” condition. Thus, to avoid estimation problems due to singularity, one demand equation must be dropped during the estimation procedure. We will drop the other foods and beverages category, and the parameters for this equation will instead be calculated using the estimated parameters of the other categories and the restrictions on model parameters that follow from the adding-up condition [12, p.4]. We will control for income and time trends in the demand model to further improve comparability across time periods. We will include these variables in the model using a scaling function procedure, following [13].

The demand equations as originally derived are complicated to estimate due to the nonlinearity of the constructed translog price index; additionally, the model suffers from biased estimates in the presence of collinearity between category prices, or an association or dependency between the explanatory price variables. To overcome these difficulties, researchers developed a linear approximation AIDS (LA-AIDS) model, which replaces the nonlinear translog price index with the linear Stone price index [14]. This approximation provides precise linearization of the underlying model when the prices of the categories are moderately collinear. We will check for price collinearity by examining variance inflation factors (VIF) of each explanatory variable. A VIF value of 1 means that there is no correlation between the variable in question and the other explanatory variables. If the VIFs are higher than 1.5, we will proceed

with the linear approximation.⁴ We can implement the LA-AIDS model and the seemingly unrelated regression method for estimating parameters for systems of equations using the `micEconAids` package [12; 16; 17] for the statistical programming language R [18]. On the other hand, if the VIFs of price variables are less than or equal to 1.5, we will conclude that little or no collinearity exists between prices. In this case, the fully nonlinear model is more appropriate [19], and we can implement it by directly coding the demand system and estimating it using the `systemfit` package and maximum likelihood estimation methods [20].

To understand changes in elasticities over time, we will estimate and compare elasticities across separate time blocks of similar length chosen to: (1) exclude major US recessions, (2) exclude the 2007-2008 global food crises, and (3) place several years between blocks to ensure a substantial difference in the number and availability of plant-based milk products in each block. Thus, our main analysis will compare elasticities from January 2002-December 2006 against elasticities from January 2015-December 2019. We will calculate both the conditional and unconditional elasticities⁵ from the demand model’s estimated parameters using the `aidsElast` function for the LA-AIDS model or manually construct the elasticities for the fully nonlinear model following [20]. We will compare the differences in calculated elasticities using a Student’s *t*-test (with a significance threshold of $\alpha = 0.10$) on the null hypothesis that the estimates are the same in the two time blocks [7]. We will check the robustness of our estimates with two additional analyses using different choices of time blocks: one following the Federal Reserve’s definition of recessions to control for the impact of recessions on our estimates (comparing October 2001-February 2007 against July 2009-December 2019), and one with similar price trends to ac-

³ Given our interest in the relationship between plant-based and dairy milks, ideally we would include a separate demand equation for plant-based milks so that we could provide our own estimates of cross-price elasticities to incorporate into our conclusions in Section 3. However, we have not identified any publicly available data on monthly sales and prices of plant-based milks similar in scope to our dairy milk data. In our demand estimation, expenditures on plant-based milks are accounted for in the other food and beverages category.

⁴ The particular VIF threshold value of 1.5 is somewhat arbitrary. There are many rough and sometimes conflicting guidelines as to what constitutes “high” levels of collinearity that are applied when using VIF for diagnostics; in reality, the other factors in the research design should be examined alongside VIF for guidance [15]. In our context, the LA-AIDS model is constructed to handle collinearity that the fully nonlinear AIDS cannot, so we only need to determine whether *some* collinearity exists in the data.

⁵ Unconditional elasticities (those that account for both the effect of a change in price as well as a change in income) are generally more useful for policy recommendations, as they consider the direct and indirect effects of a price change on consumer behavior, but conditional elasticities provide a clearer picture of the pure substitution effect of the price change.

count for the potential impact of consumer expectations of prices on elasticity estimates (comparing January 2002–December 2006 against January 2012–December 2016).⁶

4.2. Prices

The monthly price index for the other nonalcoholic beverages category and the total food and beverage category will be collected from the BLS Consumer Price Index (CPI) Urban Consumers database [21]. Following [13], the total food and beverage price index will serve as the price index for the “other foods and beverages category.”

Average retail prices for plain dairy milk will be estimated using wholesale all milk prices between 2001–2019 from the National Agricultural Statistics Service’s (NASS) *Agricultural Prices* report [22] and retail price data between 1996–1998 from Mittal et al [23]. Similar to [13], we will use ex-post predictions of average retail prices because, to the best of our knowledge, there are no publicly available monthly data between 2001–2019 that report the average retail price over all plain dairy milk products and only dairy milk products.⁷

Our ex-post prediction method will proceed as follows. We will collect the retail price data for whole, 2%, 1%, and skim milk products that are published in Appendix V of Mittal et al [23]. These data cover the 26-month period starting in January 1996, and they were collected by Mittal et al from Nielsen and various US state milk marketing agencies. We will compute the simple average of retail price over all four milk categories in all reporting cities. We will then estimate the relationship between this average retail plain milk price and wholesale all milk price from the *Agricultural Prices* report between 1996–February 1998 using either an ordinary least squares linear regression or an ARIMA model, depending on the outcome of diagnostic tests for stationarity. We will perform four diagnostic tests,

and should any one of them conclude that the data are stationary or autocorrelated, we will estimate the relationship with an ARIMA model as determined by diagnostic features included in the `auto.arima` function of the forecast package [24]. Namely, stationarity will be indicated if we fail to reject the null hypothesis of the ADF test or reject the null hypothesis of either the level or trend KPSS test; autocorrelation will be indicated if we reject the null hypothesis of the Ljung-Box test.⁸ The `auto.arima` routine estimates several different specifications of ARIMA models and reports the results for the most appropriate model according to repeated KPSS tests (to determine the number of lag differences) and the lowest Akaike Information criterion of iterated fitted models (to determine the autoregressive and moving average order). Finally, using the estimated parameters of the model, we will predict the values of average retail plain milk prices between 2001–2019 on wholesale all milk price data between 2001–2019.

To check the robustness of our retail price estimation procedure, we can predict the average retail price of whole and 2% dairy milk, a subset of products for which 2001–2019 monthly retail price data are available, and assess the accuracy of our predicted values relative to these actual data. We will collect the data from the USDA Agricultural Marketing Service’s (AMS) *Retail Milk Prices* report [25], which publishes monthly retail prices of conventional and organic whole and 2% dairy milk gathered directly from grocery stores and other retail outlets between 2001–2020. To determine the accuracy of our predictions, we will examine the mean absolute error (MAE) and the mean absolute scaled error (MASE) between our model’s fitted values and actual 2001–2019 data, with $MAE \leq 0.30$ and $MASE \geq 1$ as our criteria for an accurate prediction.⁹ Should the price prediction procedure fail to satisfy both of our MAE/MASE criteria for accuracy, we will estimate the overall demand system using only whole and 2% milks in the plain dairy milk category, allowing 1% and skim milk to fall into the other food and beverages category. Estimating this subset of the plain milk category will allow us to use directly observed retail price data; although relying solely on this analysis would limit the scope of our con-

⁶ Elasticities are constructed to measure the change in demand associated with a change in observed prices. However, this calculation does not capture the demand changes that might occur due consumer perception of these observed price changes. For example, a sharp change in price might lead consumers to believe that the price change is temporary; however, if prices remain high for a longer period of time, consumers may adjust by switching to lower-priced substitutes. Choosing time blocks with similar trends may alleviate differences in consumer expectations of future prices between the separate time blocks.

⁷ There is a CPI series covering all fluid milk prices between 1946–2020. However, BLS researchers have confirmed through personal communication that fluid plant-based beverage milks are classified in these categories alongside their dairy counterparts.

⁸ All tests will use a significance level of $p \leq 0.10$.

⁹ We choose the threshold $MAE \leq 0.30$ to allow for roughly 10% error, according to the range of observed average prices for whole and 2% milk products. MASE is constructed as a unit-free measure of error such that $MASE \geq 1$ indicates that a random walk prediction would be better than the predicting model in question. We will calculate MAE and MASE using the `Metrics` package in R.

clusions somewhat, these conclusions would still account for a significant portion of the market, as whole and 2% milk categories comprise around 75% of volume sales of the plain dairy milk category.

4.3. Expenditure shares

Along with income data, expenditure data for the other nonalcoholic beverage category and total food and beverages will be collected from the Bureau of Labor Statistics' (BLS) Consumer Expenditure (CE) survey public use micro-data files on monthly expenditure between 2001 and 2019 [26]. Data are reported for individual households, and we will take the average over each month's reported income and expenditures for each category.

Average household expenditures for the plain dairy milk category will be constructed as the product of average retail prices and total quantity sales, divided by the number of households in the US reported by the US Census Bureau [27]. Monthly total quantity sales of dairy milk are reported by AMS in the *Estimated Fluid Milk Products Sales* report, previously known as the *In-Area Sales* report [28]. These publications report total sales of consumer-packaged dairy milk products to consumer-facing outlets like retail stores, schools, and other institutions that sell packaged products directly. The reports account for all dairy milk products separately, and we will aggregate the quantity sales of the relevant products into total plain dairy milk quantity sales. The units of these quantity figures are millions of pounds of packaged milk products, which we will convert to gallons using the factor 1 gallon = 8.62 pounds, following the USDA Economic Research Service's guidelines for agricultural commodity unit conversion [29].

Total food and beverage expenditures will be used to calculate expenditure shares for each demand category as well as to estimate the expenditures for the all other food and beverages' category. We will follow the literature and calculate the all other food and beverages category by subtracting the expenditures of plain dairy milk and other nonalcoholic beverages from total food and beverage expenditures [13]. Expenditure shares will be calculated as expenditures in that category divided by total food and beverage expenditures.

4.4. Final estimation considerations

We may need to address potential price endogeneity, or bias introduced when estimating demand models in which price and quantity are determined simultaneously. We will

to check the robustness of our main specification by reporting these results alongside results from the model estimated using an instrumental variables methods; specifically, we will perform a 3-stage least squares (3SLS) procedure, using lagged prices as instrumental variables for current prices in each category.¹⁰ We will also check that lagged prices are appropriate instruments for current prices by examining the *F*-statistic for the hypothesis that the coefficients from the first stage in the 3SLS procedure are jointly statistically different from zero.¹¹ The 3SLS procedure and the *F*-statistic test have a straightforward implementation in the *micEconAids* package [17].

5. DECLARATIONS

5.1. Funding

This project is funded in part by a grant from the Food Systems Innovations Fund.

5.2. Authors' contributions

Jacob Peacock and Samara Mendez conceptualized the project. All authors developed the methodology. Samara Mendez led manuscript writing. All authors reviewed and approved the final manuscript.

¹⁰ Instrumental variables should satisfy two criteria: the variables should be correlated with the endogenous variable (prices of different categories) but uncorrelated with the outcome variable (demand for dairy milk). When time series data are available, lagged versions of variables are often used as instruments under the assumption that the previous period's price does not affect the current period's demand [12].

¹¹ A large *F*-statistic will indicate that the first-stage coefficients are statistically different from zero and therefore are relevant instruments. Should we fail to reject the null hypothesis that the joint effects of the instruments are equal to zero, we will need to collect data on different instruments, using economic theory to determine which variables might be more appropriate.

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