Agricultural and Resource Economics Review (2024), 1–20
doi:10.1017/age.2024.11

RESEARCH ARTICLE

Citrus greening, retail fruit prices, and household welfare: A demand system approach

Diansheng Dong[1], Hayden Stewart[1], Anne T. Byrne[1] and Monica Saavoss[2]

[1]US Department of Agriculture, Kansas City, MO, USA and [2]US Department of Agriculture, Washington District of Columbia, USA
Corresponding author: Diansheng Dong; Email: diansheng.dong@usda.gov

(Received 8 July 2023; revised 26 March 2024; accepted 24 June 2024)

Abstract
Pests and diseases like citrus greening that threaten agricultural productivity also pose a risk to consumers. Reductions in food supply due to outbreaks and spread could increase food prices. We model U.S. household fruit demand using a Quadratic Almost Ideal Demand System and data from Circana's 2020 and 2021 household panel. Price and income elasticity estimates reveal how household behavior might adjust with shocks to citrus and other fruit prices. Shocks to retail fruit prices can be from either citrus greening or other phenomena such as adverse weather. We also use compensating variation to estimate the impact that changes in fruit prices could have on consumer welfare.

Keywords: Citrus greening; citrus demand; consumer welfare; fruits; Huanglongbing; QUAIDS model

JEL Classification: D12; C31; C51

Introduction

Pests and diseases that threaten agricultural productivity and output also pose a threat to consumers. The Animal Plant Health Inspection Service (APHIS), an agency within the U.S. Department of Agriculture (USDA) responsible for monitoring and managing threats to all types of crops and animal agriculture, lists dozens of these diseases and pests on its website (USDA-APHIS, 2022a). Citrus greening, officially known as Huanglongbing (HLB), is among the diseases negatively affecting U.S. agriculture (APHIS, 2022b; University of Florida Citrus Research and Education Center, 2022a). It is spread by an insect, the Asian citrus psyllid. Trees can fall victim to HLB if infected insects feed on them. Symptoms include yellow shoots, leaf mottle, and small lopsided fruit that taste bitter and appear green at the stylar end. The tree will eventually die. HLB originated in Asia but has spread globally to Africa, South America, and North America. It was first detected in the U.S. in Florida in 2005.[1]

[1]HLB has been detected in all major citrus-growing states in the U.S. (USDA APHIS, 2022b; Graham et al., 2020). However, the disease is more pervasive in Florida and Texas where it has been found in all counties with commercial citrus groves (University of Florida Citrus Research and Education Center, 2022a;

Reductions in agricultural output associated with HLB, much like those associated with adverse weather events and other phenomena, can negatively affect consumer welfare. How much consumer welfare decreases will depend on the size of any increase in retail prices as well as consumer demand for affected products. The more consumers demand of those products and the less elastic their demand for them, the greater is the potential welfare loss.

A variety of techniques exist for detecting HLB, mitigating its effects, and controlling spread of the disease.[2] However, a cure has not yet been found. Thakuria et al (2023) provide a review of existing detection and management options while Zapata et al (2022) examine the disease's impact on grower profitability. Application of Zapata et al's (2022) method to a hypothetical grapefruit grove in Texas reveals that growers should expect a substantial reduction in profits once their trees become infected regardless of the strategy they implement.

Citrus fruits represent a substantial portion of U.S. total fruit consumption and damages to these crops may adversely affect consumer welfare. In 2021, U.S. per capita fruit consumption totaled about 193 pounds on a retail equivalent weight basis (USDA ERS, 2023). About 68 percent of this fruit (132 pounds) was marketed in fresh form, 24 percent (46 pounds) was sold as juice, and 8 percent (15 pounds) was sold in frozen, canned, or dried form. Citrus fruits, including oranges, tangerines, grapefruit, lemons, and limes, among others, represented 19 percent of all fresh fruit consumption and 54 percent of all fruit juice consumption.

In this study, we focus on citrus fruit, a market facing biological threats, and begin with a brief review of evolving supply and demand conditions in the U.S. market. We then present and estimate a fruit demand system. This is necessary in order to understand how demand might respond to any retail price changes. Estimation of a Quadratic Almost Ideal Demand System (QUAIDS) provides income and conditional expenditure elasticities as well as own- and cross-price elasticities of demand. Household-level data from Circana's (formerly IRI's) 2020 and 2021 National Consumer Panel (NCP) are used to estimate the demand system including: (1) citrus fresh (all whole or cut fresh citrus fruit), (2) citrus liquid (citrus juices and drinks including frozen types), (3) other fresh (all non-citrus cut or whole fresh fruit), (4) other liquid (non-citrus juices and drinks including frozen types), and (5) all others (all frozen excluding frozen liquid, dried, or canned fruit products). Finally, we use compensating variation (CV) to estimate the impact that a change in fruit prices could have on consumer welfare. Our method for calculating CV uses compensated (Hicksian) price elasticities that we obtain from our QUAIDS model. This method is easier to use than other procedures requiring estimation of the cost function.

Graham et al., 2020). There have not yet been any documented commercial losses in California (University of California, Division of Agriculture and Natural Resources, 2022; Graham et al., 2020). However, in October 2023, HLB was discovered in a residence farther north and closer to commercial groves than HLB had been previously found in California (Murtaugh, 2023). A citrus quarantine was declared by the state around that area.

[2]U.S. states with commercial citrus production, including Florida, California, Texas, and Arizona, for example, have implemented programs designed to control spread of the disease (University of Florida Citrus Research and Education Center, 2022b; University of California, Division of Agriculture and Natural Resources, 2022; Texas Citrus Pest and Disease Management Corporation, 2022; Arizona Department of Agriculture, 2022). Florida, for one, requires citrus growers, harvesters, packers, and processors to sign compliance agreements. Growers and their caretakers must agree to purchase trees from only certified nurseries and decontaminate upon exiting a grove. Nurseries are inspected every 30 days. Regulations also prohibit the movement of plants and plant parts between states from areas quarantined due to citrus greening.

Welfare calculations presented in the study for a few scenarios are based on historic data and could be adapted to account for food price shocks that may occur in the future.

U.S. citrus fruit market dynamics and the spread of HLB

U.S. growers harvested $2.91 billion worth of citrus fruit during the 2021–2022 growing season (USDA, NASS, 2022). Largest among them was the orange crop valued at about $1.47 billion followed by the tangerine and mandarin crops ($0.70 billion), the lemon crop ($0.58 billion), and the grapefruit crop ($0.17 billion).

U.S. citrus fruit growers have faced many challenges in recent decades including the spread of HLB, adverse weather events, and competition from imports (Luckstead and Devadoss, 2020). U.S. production of oranges for juicing and other forms of processing has been trending downward since the mid-2000s when HLB was first detected in the country (USDA ERS, 2022b). Growers in Florida accounted for over 90% of U.S. oranges harvested for processing in the early 2000s. Due in part to HLB, production in Florida fell from 6.4 million short tons in 2004/05 to 1.7 million short tons in 2020/21, a 72% decrease.

U.S. consumers have also been drinking less orange juice over time. U.S. per capita orange juice consumption fell 53% from 0.175 to 0.083 cups per day between 2005 and 2021 (USDA, ERS, 2023).[3] Healthcare providers, who once encouraged children to drink 100% fruit juice as a source of nutrients and extra water, have become worried about the amounts of calories and sugar in fruit juice (Heyman and Abrams, 2017). The American Academy of Pediatrics now recommends that caregivers promote whole fruit, water, and low-fat/nonfat milk as alternatives (Heyman and Abrams, 2017), even though there remains little evidence that fruit juice consumption contributes to obesity or obesity-related diseases (Auerbach et al., 2018).[4]

U.S. grapefruit production and consumption have also been declining steadily (USDA ERS, 2022b and 2023). During the 2004–2005 growing season, Florida and Texas growers accounted for a combined 82% of U.S. production. However, combined production in those two states fell from 808,000 short tons in 2004/05 to 196,000 short tons in 2021/22, a 76% decrease. For consumption, grapefruit fell 75% from 0.016 to 0.002 cups per day between 2008 and 2021 nationally.

Warnings have been issued against consuming grapefruit and grapefruit juice with certain medications as consumption of this type of citrus fruit can interfere with the performance of those drugs, including some common prescription and over-the-counter drugs for managing blood pressure and cholesterol. The U.S. Department of Health and Human Services (DHHS), U.S. Food and Drug Administration (FDA) requires manufacturers of those drugs to label their products with warnings against drinking grapefruit juice or eating raw grapefruit while taking the product (DHHS, FDA, 2023).

Unlike grapefruit and oranges for processing, U.S. production and consumption of fresh market oranges, tangerines, and lemons has been steady (USDA ERS, 2022b and 2023). HLB has so far not been detected in commercial groves in California (USDA NASS, 2022). California currently accounts for about 92% of all fresh market oranges, 96% of all lemons, and 96% of all U.S.-grown tangerines and mandarins.

[3] Estimates include orange, temple, tangerine, and tangelo juice.

[4] A review of the literature by Auerbach et al. (2018) concludes that the amount of weight gain associable with drinking 100% fruit juice is small and unlikely to be clinically significant.

Governments around the world are investing in the fight against HLB.[5] Hopefully, breakthrough technologies will be developed soon to limit damage from the disease. Retail orange and grapefruit juice prices are already increasing. Data from the Florida Department of Citrus (FDOC) show that average retail prices for 100% orange juice purchased as frozen concentrate (FCOJ) increased about 51% from $3.57 per gallon during the 2004–2005 season to $5.38 per gallon in 2020–2021 (FDOC, 2021).[6] Average retail prices for 100% orange juice purchased as refrigerated, not-from-concentrate (NFC) juice simultaneously increased 62% from $5.49 per gallon during the 2004–2005 season to $8.92 per gallon in 2020–2021 with some of the largest price increases occurring during the most recent years.[7] Indeed, according to Dezember and Uberti (2023), average retail prices for NFC juice were up 20% in January 2023 over peak prices seen in 2016. This price spike occurred after Florida announced its smallest orange crop since 1937 due to the continued spread of HLB, hurricanes, and other adverse weather conditions. The size of the spike might have been even worse for consumers if imports were not also rising to offset some lost domestic production. Imported fruit accounted for 58.4% of U.S. orange juice supply in 2021 up from 14.9% in 2004 (USDA ERS, 2022b). Brazil is the world's leading producer and exporter of oranges for processing (USDA FAS, 2022a). HLB is also pervasive in that country.[8] Any further spread of the disease, including California where the bulk of U.S. citrus fruit for consumption as fresh produce is grown, could further raise consumer-level prices for all types of citrus fruit products with negative implications for consumer welfare.

Modeling U.S. household fruit demand and potential welfare loss

U.S. households are vulnerable to food price shocks that may arise from the spread of diseases, pests, and other threats to agriculture. Up-to-date price and income elasticities of demand are needed to predict how households may adjust the mix of products they buy in response to food price shocks. A broad measure of overall household well-being is also needed. Compensating variation (CV) has been widely used in the literature to quantify changes in household welfare given a specific set of price changes. In this study, we

[5]The USDA APHIS Citrus Health Response Program (CHRP) protects the citrus industry against pests and diseases and maintain the U.S. citrus industry's ability to ship healthy citrus products within the U.S. and around the world. In 2013, the USDA APHIS established an HLB multi-agency command (MAC) response, including the USDA Agricultural Research Service (ARS), NIFA, State departments of agriculture, and others. Since FY 2014, the HLB MAC has funded over 100 projects at universities, private companies, State cooperators, and Federal agencies to address HLB (USDA, 2022). In November 2021, for example, USDA's National Institute of Food and Agriculture (NIFA) awarded $11 million to support 5 different groups of researchers including $7 million for one group spread across Texas, California, Florida, and Indiana to pursue advanced testing and commercialization of promising HLB therapies (NIFA, 2021).

[6]Retail FCOJ prices are also up in inflation-adjusted terms. The monthly-average value of the Consumer Price Index (CPI) for all items with base period 1982–1984 was 193.5 during the 2004–2005 season and 266.62 during the 2020–2021 season (U.S. Department of Labor, 2023). Both seasons lasted from October of the first year through September of the second year. To adjust for inflation, we deflated nominal FCOJ prices by the CPI. In 2004-05, FCOJ cost $1.84 per gallon ($100 \times (\$3.57 \div 193.5)$) in real 1982–1984 dollars. In 2020–2021, it cost $2.02 per gallon ($100 \times (\$5.38 \div 266.62)$) in real 1982-84 dollar, an approximately 9% real, inflation-adjusted price increase.

[7]Following the same procedures described in footnote #6 for FCOJ, we find that retail prices for NFC increased about 18% between the 2004–2005 and 2020–2021 seasons in real, inflation-adjusted terms.

[8]According to USDA, FAS (2022b), 24% trees in a major commercial area in Brazil were affected by citrus greening in 2022, an increase of 9% in greening infection relative to 2021. In 2023, Brazil was expected to ship 1.7% less orange juice to the U.S. than in 2022 (Rosen, 2023).

consider a few scenarios: first we consider a 10% price increase in any individual fruit category, holding substitute prices constant, and second, we consider simultaneous price increases in fruit categories.[9]

Several previous studies using data collected in the 1980s through the 2000s examine U.S. household demand for fruit. In general, it is found that fruit demand is inelastic. For example, Park et al.'s (1996) elasticity estimate for total fruit (aggregated) is −0.43 based on the 1987–1988 National Food Consumption Survey. Using the same data, Huang and Lin (2000) reported an estimate of −0.70. Using Nielsen Homescan data, Dong and Lin (2009) reported that the elasticity estimate for total fruits is −0.55. Price elasticities for specific fruit products are more elastic than those for the total aggregate but still are inelastic in most cases. For example, previously reported elasticity estimates for oranges are −0.85 (Huang, 1993), −0.67 (Brown and Lee, 2002), −0.79 (Durham and Eales, 2010), and −1.14 (You et al., 1997). Those for all citrus are −0.65 (Huang, 1993) and −1.10 (Okrent and Alston, 2012).

Existing studies also confirm that fruit is a normal and necessary good as the Engel curve relationship between income and total expenditure on fresh fruits is positive and less than 1. Using retail purchase data reported by Nielsen's Homescan panel, Lin et al. (2009) found that households will increase their total fresh fruit expenditures by 0.19% given a 1% increase in income. They also investigate how changes in total fresh fruit expenditures will, in turn, affect spending on organic and conventional fresh fruits. For example, a 1% increase in fresh fruit expenditure is found to increase expenditures on organic fresh fruits by 0.81% to 1.03% (the expenditure elasticity). The estimated expenditure elasticities can be multiplied by the 0.19% Engel Curve effect to estimate how much organic fruit expenditures would rise with a 1% increase in income (the income elasticity).

Given ongoing changes discussed above in U.S. demand for citrus fruit, we desire updated estimates of how consumers may respond to price increases. Indeed, during the height of the COVID-19 pandemic in 2020, U.S. demand for orange juice increased but this boost in demand was short-lived and consumption fell in 2021 over 2020 as the pandemic subsided.[10] In this study, we separately model U.S. household fruit demand using both 2020 and 2021 NCP data.[11] Results from both data sets are used to estimate the impact of an increase in retail prices on consumer welfare. To save space, we report a full set of results using 2021 data and only those essential to estimating welfare effects using 2020 data. Comparing results for the two years serves as a robustness check. It also illustrates how differences in demand conditions can lead to different estimates of how a given retail price increase might affect consumer welfare.

The NCP is an operational joint venture owned by Circana and The Nielsen Company (Muth et al. 2016). The data set includes households that participated for 12 full months and bought at least one fruit product during that year. Each household used a hand-held scanner to record its food purchases after shopping occasions at retail food stores (e.g., supermarkets, supercenters, and warehouse club stores). We identify and place each NCP household's fruit purchases into one of 5 categories: (1) citrus fresh (all whole or cut

[9]According to Dezember and Uberti (2023), retail juice prices in January 2023 were up more than 20% over highs reached in 2016. To be conservative, we simulate the impact of 10% price increases in this study.

[10]The FDOC is working to promote orange and grapefruit juice consumption. The department's efforts include "The Original Wellness Drink," a generic advertising campaign (FDOC, 2021). The campaign highlights the nutritional benefits of 100% orange juice including hydration, immune system support, and heart health. It is likely that consumers seeking to bolster their immune strategy sought out orange juice as a source of Vitamin C which is known to support one's immune system.

[11]2021 is the most recent data available to us.

Table 1. Household fruits expenditures, prices, and quantities, 2021

Product	Expenditure (dollars)	Quantity (oz)	Probability (Quantity = 0)	Price (dollars/oz)	Expenditure share
Total Fruits	234.95	1684.39	0	0.139	1.00
Citrus -fresh	19.45	216.11	0.23	0.09	0.09
Citrus-liquid	18.42	263.14	0.30	0.07	0.08
Other-fresh	152.35	725.48	0.01	0.21	0.61
Other- liquid	23.15	385.83	0.26	0.06	0.10
All-others	21.58	93.83	0.12	0.23	0.12

Note: (1) citrus fresh are all whole or cut fresh citrus fruits, (2) citrus liquid are citrus juices and drinks including frozen types, (3) other fresh are all non-citrus cut or whole fresh fruits, (4) other liquid is non-citrus juices and drinks including frozen types, and (5) all others are all frozen excluding liquid, dried, or canned fruit products. Total households in the sample = 53,732.

Table 2. Household fruits expenditures, prices, and quantities, 2020

Product	Expenditure (dollars)	Quantity (oz)	Probability (Quantity = 0)	Price (dollars/oz)	Expenditure share
Total Fruits	231.01	1692.65	0	0.136	1.00
Citrus -fresh	19.61	218.37	0.23	0.09	0.09
Citrus-liquid	19.59	283.09	0.30	0.07	0.08
Other-fresh	151.45	778.66	0.01	0.19	0.63
Other- liquid	20.35	316.17	0.26	0.06	0.11
All-others	20.01	96.34	0.12	0.21	0.09

Note: (1) citrus fresh are all whole or cut fresh citrus fruits, (2) citrus liquid are citrus juices and drinks including frozen types, (3) other fresh are all non-citrus cut or whole fresh fruits, (4) other liquid is non-citrus juices and drinks including frozen types, and (5) all others are all frozen excluding liquid, dried, or canned fruit products. Total households in the sample = 54,645.

fresh citrus fruit), (2) citrus liquid (citrus juices and drinks including frozen types), (3) other fresh (all non-citrus cut or whole fresh fruit), (4) other liquid (non-citrus juices and drinks including frozen types), (5) all others (all frozen excluding frozen liquid, dried, or canned fruit products). Finally, we calculate each household's 2020 and 2021 annual fruit purchases within each category by aggregating over their daily purchases. This Circana data set enables us to measure fruit demand and consumer welfare at the household level.

Some NCP households reported no purchases of some fruit products in our demand system (Tables 1 and 2). For example, in 2021, among all 53,737 sampled households, about 23% bought no citrus fresh, 30% did not buy citrus liquid, 1% made no purchases of other fresh, 26% did not acquire other liquid, and 12% did not buy all others. The data are censored at zero. We cannot fully observe household demand in all cases.

Estimates of the prices that each household faced for all 5 products were derived as is necessary for the estimation of a demand system. For those fruit products that households reported buying, we use unit values calculated from the observed expenditure and purchase quantities. These data suffer from "data censoring" whereby some households purchase zero items in the target categories so prices and demand cannot be directly observed. Censoring is often unavoidable in household demand models but can be addressed with established methods. For missing price observations, which occur when households reported zero purchases of a product, we first use the average unit value paid by households in the same zip code. If no other households residing in the zip code made a purchase, we then use the average unit price paid by households in the same county, followed by households in the same state, and, finally, households across the nation. For the 2021 data, the average unit values paid for fruit are \$0.139/oz for total fruit, \$0.09/oz for citrus fresh, \$0.07/oz for citrus liquid, \$0.21/oz for other fresh, \$0.06/oz for other liquid, and \$0.23/oz for all others (Table 1).

The QUAIDS model introduced by Banks et al. (1997) is adopted in the study. The QUAIDS model is well suited for modeling annual U.S. household demand for a group of fruit products. This model extends Deaton and Muellbauer's (1980) Almost Ideal Demand System (AIDS). The AIDS model is consistent with economic theory as it satisfies most axioms of consumer choice. However, it assumes a consumer's purchases of each individual product to be loglinear in total expenditure on the group. The QUAIDS model further allows for the possibility that such consumer behavior is quadratic in log total expenditure. Additionally, it can also be adapted to correct for problems associated with use of scanner data, such as expenditure and price endogeneity and data censoring. Estimated elasticities from the QUAIDS model calculated with more recent data will generate superior CV estimates than relying on published, older estimates would have.

Fruit demand model

Following classic economic theory and previous analyses of U.S. food demand, we assume that households engage in a multistage budgeting process and fruits are separable from other goods. Households first allocate their income across housing, transportation, food away from home, and different food groups for food at home (FAH), such as fruits, vegetables, meats, and grains, among other needs and wants. Money allocated to a FAH group in the first stage is then divided among specific types of products in a second stage. It can be theorized that total FAH fruit expenditures are divided in the model's second stage among the 5 fruit products mentioned above.

Empirical analyses of food demand typically focus on only one stage of a household's budgeting process. In this study, we followed that same general approach. We focused on the second stage and did not attempt to estimate a complete first-stage system; rather, we simplified the first stage to a single equation that explains a household's total FAH fruit expenditures in 2020 and 2021. In keeping with economic theory, we include household income in this equation. Based on a review of past studies, we also include selected demographic characteristics such as household size, education, and race (USDA ERS, 2022a; Hoy et al., 2017; Tichenor and Conrad, 2015; Drewnowski and Rheem, 2015). This single equation is called the Engel curve and it reveals the relationship between income and total fruit expenditures.

Following Dhar et al., (2003), we specify our total fruit expenditure equation in log form as:

$$lnX = \delta' Y + \eta \tag{1}$$

where X is average household-level FAH total fruit expenditures and Y is a J $\times$ 1 vector of explanatory variables. δ is a vector of parameters [J $\times$ 1], and η is an error term. As mentioned above, we included in Y household income and other household demographic variables.

To model the second stage of the multistage budgeting process and explain how households spread their total fruit expenditures over the five categories of products, we

https://doi.org/10.1017/age.2024.11 Published online by Cambridge University Press

estimated a demand model based on the QUAIDS first introduced by Banks et al. (1997). A basic system of five QUAIDS expenditure share equations is:

$$W = \alpha + \gamma ln\, P + \ \beta\, ln\left(\frac{X}{a(P)}\right) + \frac{\lambda}{b(p)}\left(ln\left(\frac{X}{a(P)}\right)\right)^2 + \varepsilon \tag{2}$$

where W is a 5×1 vector of expenditure shares, lnP is a 5×1 vector of log product prices, lnX is log total fruit expenditures, $lna(P) = \alpha_0 + \ \alpha' lnP + \ \frac{1}{2}\ (lnP)'\gamma(lnP),, b(P) = e^{\beta' lnP}$, and ε is a 5×1 vector of error terms where $\varepsilon \sim N(0, \Sigma)$. The error term follows a joint normal distribution with a mean vector of 0 and a variance-covariance matrix Σ.

The model contains a group of parameters to be estimated: α_0 $[1 \times 1]$,[12] α $[5 \times 1]$, β $[5 \times 1]$, λ $[5 \times 1]$, γ $[5 \times 5]$, and $\Sigma[5 \times 5]$. As shown in (2), W is quadratic in log total expenditure X if λ is statistically significant. If not, the QUAIDS budget share equations reduce to the AIDS budget share equations and W is linear in log X.

To ensure the model conforms with economic theory, the following restrictions are placed on the parameters: $I\alpha = 1,\ \mathbf{I}\gamma = 0,\ \ I\beta = 0, I\lambda = 0, I\Sigma = 0,\ \ \gamma' = \gamma$ where I is a $5{\times}1$ vector of 1's.[13]

We allowed for the likelihood that households' fruits choices depended on their demographic characteristics in addition to prices and expenditures. It is possible to incorporate such variables into the above QUAIDS by transforming the intercept in equation (2), α, as:[14]

$$\alpha = \vartheta_0 + \vartheta_1 Z \tag{3}$$

where Z is $[k \ \times \ 5]$ vector of demographics and k is the number of such variables. Inserting equation (3) into equation (2) completes the specification of our demand model for the second stage of a household's budgeting process:

$$W = \vartheta_0 + \vartheta_1 Z + \gamma lnP + \ \beta\, ln\left(\frac{X}{a(P)}\right) + \frac{\lambda}{b(p)}\left(ln\left(\frac{X}{a(P)}\right)\right)^2 + \varepsilon. \tag{4}$$

Following previous studies, we include in Z variables such as household size, age, race and ethnicity, and education (USDA ERS, 2022a; Hoy et al., 2017; Tichenor and Conrad, 2015; Drewnowski and Rheem, 2015). ϑ_0 $[5 \ \times \ 1]$ and ϑ_1 $[5 \times k]$ are parameter vectors. ϑ_0 and ϑ_1 have the following restrictions: $I\vartheta_0 = 1$ and $I\vartheta_1 = 0$.

The above household fruit demand model can be estimated using maximum likelihood techniques and the procedure in Wales and Woodland (1983) and Dong et al. (2004) to accommodate zero censoring as some households made no purchases of one or more of the 5 categories of fruit in our demand system as noted above (Tables 1 and 2). This procedure is unique among methods that account for data censoring because budget constraints are imposed in both the observed expenditure shares and the latent expenditure shares. Equations (1) and (4) are jointly determined. This approach helped to ensure parameter estimates were consistent as total fruits expenditure X in (4) may be endogenous (LaFrance, 1993). Marshallian price elasticities, total FAH fruit expenditure elasticities, and demographics elasticities can all be obtained using the estimate of equation (4) (Dong

[12]We normalized α_0 to 0 in our model estimation.

[13]These restrictions ensure adding up, homogeneity, and symmetry.

[14]This way of accounting for household demographic effects is called demographic translating, which allows demographics to change the level of demand but not to alter the slope. Note this makes demographic heterogeneity enter the demand system linearly via the intercept in equation (2) but also non-linearly through households' expenditures via the price index $lna(P)$ (Pollak and Wales, 1981; Lecocq and Robin, 2015).

Table 3. Demographic variables in expenditure share and total expenditure equations, 2021

Variable name	Description	Mean	Standard deviation
Intercept*	Intercept	1.00	0.00
Age_head*	Age of household head	57.60	13.42
HHsize*	Number of persons in households	2.38	1.27
College*	=1 if household head having college education or above	0.47	0.50
White*	=1 if household head is White	0.78	0.42
Black*	=1 if household head is Black	0.12	0.32
Asian*	=1 if household head is Asian	0.04	0.21
Single*	=1 if single person household	0.24	0.43
Owner*	=1 if own a house	0.77	0.42
Midwest*	=1 Midwest	0.25	0.43
South*	=1 if South	0.39	0.49
West*	=1 if West	0.19	0.39
Age_5**	=1 if having person younger than 6	0.05	0.22
Age_6_13**	=1 if having person between 6 and 13	0.10	0.30
Income**	Household income ($1,000)	67.85	36.01

*indicates in both equations, and **indicates in total expenditure equation only.

et al., 2004). The demographics included in Z and Y, as well as their summary statistics, are provided for our 2021 data in Table 3. Those for our 2020 data are available on request.

Compensating variation (welfare analysis)

Economists commonly estimate demand systems to gain important insights on consumer demand behavior and well-being. Elasticity estimates with respect to the appropriate variables can shed light on how consumers might adjust their purchases with changes in prices, expenditures, or even their own demographic characteristics such as education or household composition. It is also possible to estimate how much a change in prices can affect a consumer's overall well-being (utility). A utility function measures the well-being that a consumer experiences based on the amounts of products consumed. An indirect utility function measures optimized consumer utility based on the consumer's utility-maximizing selection of products, which is in turn based on products' prices and expenditures. For instance, higher prices imply a lower level of utility given any constant level of expenditures since prices determine the amounts of products that can be purchased and consumed with a fixed amount of money.

CV is a method for measuring changes in welfare given a change in product prices and it is based on the indirect utility function. The indirect utility function associated with a QUAIDS model (Banks et al.,1997) is:

$$u(X,P)=\left\{\left[\frac{\ln X-lna(P)}{b(P)}\right]^{-1}+L(P)\right\}^{-1} \tag{5}$$

where the variables and parameters are defined above and $L(P)=\lambda' lnP$. Given an initial level of total expenditure, X_0, and an initial set of prices P_0, $u(X_0,P_0)=\left\{\left[\frac{\ln X_0-lna(P_0)}{b(P_0)}\right]^{-1}+L(P_0)\right\}^{-1}$ is the initial level of consumer utility. This will decrease if prices increase from P_0 to P_1. The consumer could no longer afford as many goods as previously. Additional income would be required to keep the consumer's level of utility unchanged. CV is the amount of additional income needed to restore utility to its original level given new prices faced by the consumer. Let X_1 be the level of expenditures a consumer would need to attain the same level of utility as was attainable with X_0 and P_0 given the new price level, P_1. The *CV* can then be calculated as X_1 - X_0 where the value of X_1 can be determined from the function (Attanasio et al., 2013):

$$\left\{\left[\frac{lnX_1-lna(P_1)}{b(P_1)}\right]^{-1}+L(P_1)\right\}^{-1}=\left\{\left[\frac{lnX_0-lna(P_0)}{b(P_0)}\right]^{-1}+L(P_0)\right\}^{-1} \tag{6}$$

However, this well-known procedure for calculating CV is not computationally friendly. Firstly, one needs to know or estimate all parameters of the cost function (5). Secondly, one needs to solve the highly non-linear equation (6).

An alternative procedure for calculating CV is desirable as the estimation of the cost function for a food demand system at the household level is difficult. By contrast, suppose we have only price elasticities without knowing the cost function, we can still calculate the CV from the following procedure: We begin by rewriting (5) with X as a function of u and P, i.e., $X(u,P)$. This function is known as the expenditure or cost function and, as above, $CV=X_1$ - $X_0=X(u,P_1)-\ X(u,P_0)$ is the amount of income a consumer would need to keep utility constant after an increase in P from P_0 to P_1 (Huang and Huang, 2012). Following Huang and Huang (2012), we then derive the needed expenditure changes for each of the five fruit products (CV for individual products) to keep the original utility level from the expenditure function approach as below:

$$EX=(P_1Q_0)\left[\psi\ \left(dP/P_0\right)\right]+(P_0Q_0)\left(dP/P_0\right) \tag{7}$$

where EX is a 5×1 vector of the needed individual expenditure changes or the individual CV of each product in the system, ψ is a $[5\times 5]$ matrix of Hicksian price elasticities which can be calculated from the Marshallian price elasticities using the Slutsky equation after the QUAIDS model has been estimated and parameters in (4) are known, P_0 is a 5×1 vector of original prices, P_1 is a 5×1 vector of prices after the change, $dP=P_1-P_0$, and Q_0 is a 5×1 vector of original quantities purchased. CV is the sum of the 5 elements in EX.

Equation (7) takes advantage of the compensated (Hicksian) price elasticities and, in practice, should be easier to estimate than equation (6) after we have those estimates.[15] Different from the traditional indirect utility approach, in addition to CV, this approach can also provide *EX*, the expenditure changes in each individual product in the system (individual CV) to keep the original utility level given the price changes.[16]

[15]To calculate *CV* using (7), the indirect utility function or the expenditure function is not needed if we already have Hicksian price elasticities from, for example, a previously published study.

[16]For a conditional demand system for a separable group of products as used in this study, the CV analysis is only for fruit products.

Results

We estimated a QUAIDS model for U.S. household fruit demand using both 2020 and 2021 NCP data as described above. The quadratic parameter (λ) was statistically significant at the 5% level using both data sets. A quadratic relationship between total fruit expenditures and all 5 budget shares is appropriate. A QUAIDS specification better explains household behavior than a traditional AIDS would have. Parameter estimates based on our 2021 data for both the first and second stage of a household's multistage budgeting process are reported in the appendix tables (Tables A1 and A2). Those based on our 2020 data are available on request. Results based on the two data sets are expected to differ somewhat given differences in fruit product demand in 2020 and 2021. As shown above in Tables 1 and 2, U.S. households purchased slightly less fruit in 2021 (1,684.39 oz) than in 2020 (1,692.65 oz). Citrus juices, such as orange juice, were among the products they bought in greater quantities during the height of the COVID-19 pandemic (19.59 oz in 2020 versus 18.42 oz in 2021). Below, we begin by reporting the estimated own- and cross-price elasticities. We then examine demand elasticities with respect to total fruit expenditures and income before turning to those with respect to a household's key demographic characteristics. Finally, we examine results for a series of simulations that show how price shocks might alter consumer welfare.

Price elasticities

Results confirm that U.S. household demand for fruit is generally inelastic with respect to own price. As shown in Tables 4 and 5, which reports the estimated Marshallian (uncompensated) price elasticities for 2021 and 2020, respectively, the own-price demand elasticities range from −0.377 for all other fruits to −0.843 for citrus fresh (Table 4 for 2021) and −0.320 for all other fruits to −0.737 for citrus fresh (Table 5 for 2020). These numbers also show that own-price elasticities are slightly smaller in magnitude in 2020 than in 2021, indicating household purchases were less responsive to price changes during the height of the COVID-19 pandemic. However, results for both years continue to be consistent with estimates reported for total fruit in previous studies: −0.43, −0.70, and −0.55 reported by Park et al. (1996), Huang and Lin (2000), and Dong and Lin (2009), respectively. Estimates previously reported for all citrus fruit include −0.65 (Huang, 1993) and −1.10 (Okrent and Alston, 2012). Estimates reported in the literature for specific types of fruit are notably higher. For example, those reported for oranges include −0.85 (Huang, 1993), −0.67 (Brown and Lee, 2002), and −0.79 (Durham and Eales, 2010).

The Hicksian (compensated) price elasticities contained in Tables 6 and 7 are essential input information in quantifying the consumer welfare effects of price changes. These are calculated using the Slutsky equation from the Marshallian price elasticities and the total expenditure elasticities and hold utility constant. The compensated own-price elasticities are smaller in magnitude than their Marshallian (uncompensated) counterparts and range from −0.155 for all other fruits to −0.749 for citrus fresh for 2021. Similar to the Marshallian price elasticities, these Hicksian own-price elasticities are smaller in magnitude in 2020 than their counterparts in 2021.

U.S. households also have only a limited willingness to substitute between different types of fruit when prices change. Positive off-diagonal values in Table 4 or 5, indicate that two types of fruit are gross price substitutes. For example, a 10-percent increase in the price of citrus liquid would increase purchases of other liquid by 1.76% for 2021 (Table 4). The Hicksian (compensated) cross-price effects reported in Tables 6 and 7 are slightly larger than their gross counterparts. A 10-percent increase in the price of citrus liquid would

Table 4. Marshallian price and expenditure elasticities of fruits, 2021

	With price of					
Demand of	citrus fresh	citrus liquid	other fresh	other liquid	all others	Total expenditure
citrus fresh	**−0.843**	**−0.131**	**0.091**	**−0.252**	**0.044**	**1.091**
citrus liquid	−0.013	**−0.805**	**−0.094**	**−0.104**	**−0.097**	**1.113**
other fresh	**0.034**	**−0.193**	**−0.733**	**−0.138**	**0.093**	**0.936**
other liquid	0.076	**0.176**	**−0.126**	**−0.495**	**−0.470**	**0.839**
all others	**−0.097**	**−0.123**	**−0.014**	**−0.276**	**−0.377**	**0.886**

Note: Bold numbers represent "significant" at 5 percent or above.

Table 5. Marshallian price and expenditure elasticities of fruits, 2020

	With price of					
Demand of	citrus fresh	citrus liquid	other fresh	other liquid	all others	Total expenditure
citrus fresh	**−0.737**	**−0.170**	**0.088**	**−0.282**	**0.031**	**1.070**
citrus liquid	−0.020	**−0.697**	**−0.107**	**−0.208**	**−0.064**	**1.094**
other fresh	**0.025**	**−0.272**	**−0.614**	**−0.155**	**0.077**	**0.938**
other liquid	0.096	**0.102**	**−0.159**	**−0.433**	**−0.454**	**0.849**
all others	**−0.082**	**−0.180**	**−0.033**	**−0.282**	**−0.320**	**0.897**

Note: Bold numbers represent "significant" at 5 percent or above.

Table 6. Hicksian price elasticities of fruits, 2021

	With price of				
Demand of	citrus fresh	citrus liquid	other fresh	other liquid	all others
citrus fresh	**−0.749**	**0.161**	**0.121**	**0.149**	**0.318**
citrus liquid	**0.177**	**−0.671**	**0.069**	**0.271**	**0.155**
other fresh	−0.086	−0.047	**−0.517**	**0.278**	**0.371**
other liquid	**0.095**	**0.296**	**0.162**	**−0.238**	**−0.315**
all others	**0.086**	**0.057**	**0.285**	**−0.274**	**−0.155**

Note: Bold are statistically significant at the 5-percent level or above.

increase compensated purchases of other liquid by 2.96% percent for 2021. Other liquid and other fresh are also substitutes.

Conditional expenditure and income elasticities

The estimated income and expenditure elasticities for 2021 reported in Table 8 reveal how changes in income may affect U.S. household fruit demand. Results for the first stage of a

https://doi.org/10.1017/age.2024.11 Published online by Cambridge University Press

Table 7. Hicksian price elasticities of fruits, 2020

	With price of				
Demand of	citrus fresh	citrus liquid	other fresh	other liquid	all others
citrus fresh	**−0.639**	**0.149**	**0.095**	**0.106**	**0.288**
citrus liquid	**0.111**	**−0.463**	**0.066**	**0.033**	**0.253**
other fresh	−0.066	−0.022	**−0.423**	**0.251**	**0.259**
other liquid	**0.039**	**0.310**	**0.179**	**−0.185**	**−0.344**
all others	**0.059**	**0.038**	**0.116**	**−0.106**	**−0.107**

Note: Bold are statistically significant at the 5-percent level or above.

Table 8. Fruit Income Elasticities of Sampled Households, 2021

	Conditional total expenditure elasticates	Income elasticities
	Income elasticity of total fruit expenditure: 0.18	
citrus fresh	1.09	0.19
citrus liquid	1.11	0.20
other fresh	0.94	0.17
other liquid	0.84	0.15
all others	0.89	0.16

household's multistage budgeting process confirm a positive Engel curve relationship between income and total fruit expenditures. A 1% increase in income increases total fruit spending by 0.18%, on average, which is very close to Lin et al (2009)'s finding of 0.19%. This result is also statistically significant at the 1% level. Results for the second stage of a household's budgeting process are reported in the first column of Table 8 and further reveal how a change in conditional expenditures, in turn, affects demand for each type of fruit in the system. A 1% increase in total fruit expenditures increases citrus fresh spending by 1.09%, spending for citrus liquid by 1.11%, spending for other fresh by 0.94%, spending for other liquid by 0.84%, and spending on all others 0.89%. Finally, our first and second-stage results are combined to estimate unconditional income elasticities of demand. Each expenditure elasticity in the first column is multiplied by the 0.18% Engel Curve effect. As shown in the second column of Table 8, a 1% increase in income increases a household's expenditures on citrus fresh by 0.19%, and citrus liquid by 0.20%. Results for 2020 are similar and available upon request.

Household demographic elasticities

In addition to prices and income, U.S. fruit demand also varies across households with their demographic characteristics. Following past studies, as mentioned above, we account for a variety of these demographic characteristics. Elasticities with respect to those variables for 2021 are provided in Table 9. Household size is found to have a positive effect on demand for citrus liquid but a negative effect on demand for other liquid. Education

https://doi.org/10.1017/age.2024.11 Published online by Cambridge University Press

Table 9. Demographic elasticities of fruit expenditure shares, 2021

	Product				
Variables	citrus fresh	citrus liquid	other fresh	other liquid	all others
Age_head	**−0.120**	−0.003	**0.044**	**0.091**	**−0.070**
HHsize	0.045	**0.216**	0.018	**−0.242**	0.016
College	**−0.014**	**−0.031**	−0.008	**0.042**	−0.002
White	**−0.040**	**−0.068**	0.003	**0.108**	**−0.033**
Black	**0.015**	0.001	**0.010**	**−0.014**	0.001
Asian	**−0.006**	**−0.008**	0.002	**0.006**	**0.003**
Single	**−0.035**	0.008	0.010	−0.004	**0.007**
Owner	**−0.017**	−0.005	**−0.023**	**0.029**	−0.003
Midwest	**0.022**	**0.024**	0.006	**−0.036**	0.001
South	**0.017**	**0.030**	0.002	**−0.034**	−0.003
West	0.000	**0.005**	**0.009**	**−0.020**	**0.012**

Note: Bold numbers are significant at the 5-percent level or above. Numbers for the dummy variables are the percentage change in the shares when the variables change from 1 to 0. The region base is Northeast.

negatively (positively) affects demand for citrus (other) liquid. Results for 2020 are similar and available upon request.

Household welfare simulations

Any further spread of HLB or other diseases or pests could negatively affect US fruit production. Parallel changes in overseas production would serve to amplify any impacts on domestic production. Below, using equation (7), we calculate the change in household welfare associated with some retail price increase scenarios. Our estimated welfare changes are in nominal dollars and will depend on initial prices, initial quantities, and our assumed demand elasticities as shown in the formula. We report two sets of simulations for the purpose of comparison. The first shows the impact on household welfare if the retail price increases were to occur when demand conditions are similar to those observed in 2021. It is based on our results using 2021 NCP data and the initial conditions reported in Table 1 for that same year. The second shows the impact on household welfare if the price increases were to instead occur in an environment more like 2020. It is based on our results using 2020 NCP data and the initial conditions reported in Table 2. Fruit prices were generally higher in 2021 ($0.139 per ounce) than in 2020 ($0.136 per ounce) (Tables 1 and 2). However, on average, U.S. households purchased slightly less fruit, including less citrus juices, such as orange juice, in 2021 than in 2020.

For our first price change scenario, we consider a 10% increase in the price of any single fruit category, holding other fruit prices constant (Tables 10 and 11). As mentioned above, retail juice prices were up to more than 20% in early 2023 over peaks reached in 2016. To be conservative, we simulate the impact of 10% price increases. Shown in the first column of Tables 10 and 11 are the effects of a 10% increase in the price of only citrus fresh. The total welfare (CV) is $0.90 for 2021 and $0.77 for 2020. Bringing households back to their initial level of utility would require increasing their average total fruit expenditures by these

Table 10. Change in compensated expenditures (compensating variation) needed to maintain household utility after A 10% price increase in individual fruits ($), 2021

	10% increase in price of				
Products	citrus fresh	citrus liquid	other fresh	other liquid	all others
citrus fresh	0.34	0.32	0.24	0.29	**0.62**
citrus liquid	0.33	0.48	0.13	0.50	**0.48**
other fresh	−0.22	−0.51	3.61	3.65	**3.69**
other liquid	0.22	0.69	0.88	1.73	**−0.74**
all others	0.22	0.15	0.74	−0.31	**2.71**
total	0.90	1.13	5.59	5.86	**6.77**

Table 11. Change in compensated expenditures (compensating variation) needed to maintain household utility after A 10% price increase in individual fruits ($), 2020

	10% increase in price of				
Products	citrus fresh	citrus liquid	other fresh	other liquid	all others
citrus fresh	0.58	0.29	0.19	0.21	**0.56**
citrus liquid	0.22	0.96	0.13	0.06	**0.50**
other fresh	−0.27	−0.33	4.06	3.78	**3.90**
other liquid	0.09	0.71	0.41	1.84	**−0.79**
all others	0.16	0.10	0.31	−0.28	**2.35**
total	0.77	1.74	5.09	5.61	**6.51**

amounts. For 2021, this includes a $0.34 increase in compensated expenditures (individual CV) for citrus fresh (due to its compensated own-price effect), $0.33 for citrus liquid (due to its compensated cross-price effect), −$0.22 for other fresh, $0.22 for other liquid, and $0.22 for all others. The negative compensated expenditure change for other fresh (−$0.22) is due to the negative compensated cross-price elasticity between citrus fresh and other fresh, a complement relationship between the two. An increase in only citrus liquid prices would have a similar impact on household welfare as shown in the second column of Table 10 for 2021. Increasing the price of these products by 10% would reduce household total welfare by $1.13. This includes a $0.48 increase in compensated expenditures for citrus liquid (due to its compensated own-price effect), $0.32 for citrus fresh (due to its compensated cross-price effect), −$0.51 for other fresh, $0.69 for other liquid, and $0.15 for all others.

By comparing Tables 10 and 11, we see that the simulated welfare losses for 2021 and 2020 are generally similar in size. One notable difference between the two sets of simulations is the effects of an increase in citrus liquids prices. This is due in large part to households' greater demand for citrus juices in 2020 as compared with 2021.

For our second price change scenario, we examine the loss in consumer welfare that could occur if price for all or some types of fruit were to simultaneously increase. Thus, we

Table 12. Change in compensated expenditures (compensating variation) needed to maintain household utility after A 10% price increase in all or combined fruits ($), 2021

Products	Prices of all fruits are increased by 10%	Prices of fresh and liquid citrus are increased by 10%
citrus fresh	1.96	**0.69**
citrus liquid	1.84	**0.94**
other fresh	8.31	**−1.03**
other liquid	2.34	**0.92**
all others	2.60	**0.37**
total	17.05	**1.89**

Table 13. Change in compensated expenditures (compensating variation) needed to maintain household utility after A 10% price increase in all or combined fruits ($), 2020

Products	Prices of all fruits are increased by 10%	Prices of fresh and liquid citrus are increased by 10%
citrus fresh	1.95	0.90
citrus liquid	1.96	1.20
other fresh	8.05	−1.33
other liquid	2.30	0.80
all others	2.66	0.26
total	16.92	1.83

calculated the CV for each of the fruits for two scenarios: (1) when prices of all five fruit product categories increased by 10%, and (2) when prices of two products, citrus fresh and citrus liquid, increased by 10% at the same time. The results are provided in Tables 12 for 2021 and 13 for 2020. In scenario (1), the consumer welfare loss is $17.05 for 2021 and $16.92 for 2020. In scenario (2), the consumer welfare loss is $1.89 for 2021 and $1.83 for 2020. The welfare loss in these two scenarios for 2021 and 2020 are again similar.

Conclusions

Researchers around the world are working to cure and mitigate the effects of HLB while U.S. states with commercial citrus production do their best to control spread of the disease. Any further spread of HLB could reduce supply of US domestic as well as foreign-grown citrus fruit while any cure could increase supply. It is currently unknown what the future holds. As such, in this study, we estimate a QUAIDS model for U.S. household fruit demand to provide the information needed to understand households' likely responses to future fruit price changes as well as the tools needed to calculate how their welfare might be affected. The method we present for calculating CV in this study can be adapted using the reported Hicksian elasticities to account for actual future events. It does not require calculating the expenditure function. Overall, the welfare losses reported in this study are relatively small compared to those reported by Dong et al. (2022) for meat products, which reflects differences in U.S. household demand for each type of food. For example, if demand conditions for fruit were like those in 2021, a 10% increase in cut or whole citrus fruit prices would reduce U.S. household welfare by \$0.90. Looking to the future, as the size and direction of coming price changes may be different, it may be necessary to accordingly re-calculate the CV.

Data availability statement. The Circana data used in the study are proprietary and can not be shared publicly.

Competing interests. The authors declare none.

Disclaimer. The findings and conclusions in this article are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy. This research was supported in part by the USDA, Food Market Branch, Economic Research Service.

References

Arizona Department of Agriculture (2022) Link: Citrus | Arizona Department of Agriculture (az.gov). Available at https://agriculture.az.gov/plantsproduce/what-we-grow/citrus

Attanasio O, Di Maro V and Phillips D (2013) Welfare consequences of food price increases: evidence from rural Mexico. *Journal of Development Economics* **104**, 136–151.

Auerbach BJ, Dibey S, Vallila-Buchman P, Kratz M and Krieger J (2018) Review of 100% fruit juice and chronic health conditions: implications for sugar-sweetened beverage policy. *Advances in Nutrition* **9**(2), 78–85. doi: 10.1093/advances/nmx006.

Banks J, Blundell R and Lewbel A (1997) Quadratic Engel curves and consumer demand. *Review of Economics and Statistics* **79**(4), 527–539.

Brown M and Lee J (2002) Restrictions on the effects of preference variables in the Rotterdam model. *Journal Agriculture and Applied Economics* **34**(1), 17–26.

Deaton A and Muellbauer J (1980) An almost ideal demand system. *The American Economic Review* **70**(3), 312–326.

Dezember R and Uberti D (2023) Why orange juice is so expensive right now. *The Wall Street Journal.*

Dhar T, Chavas JP and Gould BW (2003) An empirical assessment of endogeneity issues in demand analysis for differentiated products. *American Journal of Agricultural Economics* **85**(2), 605–617.

Dong D, Gould BW and Kaiser HM (2004) Food demand in Mexico: an application of the Amemiya-Tobin approach to the estimation of a censored food system. *American Journal of Agricultural Economics* **86**(4), 1094–1107.

Dong D and Lin B (2009) *Fruit and Vegetable Consumption by Low-Income Americans, Would a Price Reduction Make a Difference?* ERR-70, U.S. Department of Agriculture, Economic Research Service.

Dong D, Stewart H, Dong X and Hahn W (2022) Quantifying Consumer Welfare Impacts of Higher Meat Prices During the COVID-19 Pandemic. ERR-306, U.S. Department of Agriculture, Economic Research Service.

Drewnowski A and Rheem C (2015) Socioeconomic gradient in consumption of whole fruit and 100% fruit juice among US children and adults. *Nutrition Journal* **14**(3). https://doi.org/10.1186/1475-2891-14-3

Durham C and Eales J (2010) Demand elasticities for fresh fruit at the retail level. *Applied Economics* **42**(11), 1345–1354.

Florida Department of Citrus (2021) 2021 Citrus Reference Book. Page 65. Available at https://app.box.com/embed/s/dt42f2c7kk

Graham J, Gottwald T and Setamou M (2020) Status of Huanglongbing (HLB) outbreaks in Florida, California and Texas. *Tropical Plant Pathology* **46**, 265–278. https://doi.org/10.1007/s40858-020-00335-y.

Heyman MB and Abrams SA (2017) Fruit juice in infants, children, and adolescents: current recommendations. *Pediatrics* **139**(6), e20170967. doi: 10.1542/peds.2017-0967

Hoy MK, Goldman JD and Moshfegh AJ (2017) Differences in fruit and vegetable intake of U.S. adults by sociodemographic characteristics evaluated by two methods. *Journal of Food Composition and Analysis* **64**, 97–103.

Huang KS and Huang SW (2012) Consumer welfare effects of increased food and energy prices. *Applied Economics* **44**(19), 2527–2536.

Huang K and Lin B (2000) Estimation of food demand and nutrient elasticities from household survey data. Technical Bulletin No. 1887, U.S. Department of Agriculture, Economic Research Service, August.

Huang K (1993) A Complete System of U.S. Demand for Food, *TB*-1821, U.S. Department of Agriculture, Economic Research Service, September.

LaFrance JT 1993. Weak separability in applied welfare analysis. *American Journal of Agricultural Economics*, **75**(3), 770–775.

Lecocq S and Robin JM (2015) Estimating almost ideal demand systems with endogenous regressors. *The Stata Journal* **15**(2), 554–573.

Lin B, Yen ST, Huang CL and Smith TA (2009) U.S. demand for organic and conventional fresh fruits: the roles of income and price. *Sustainability* **1**, 464–478. https://doi.org/10.3390/su1030464.

Luckstead J and Devadoss S (2020) Trends and issues facing the U.S. citrus industry. *Choice* **38** (2), 1–10. cmsarticle_775.pdf (choicesmagazine.org)

Murtaugh I (2023) Tree killer' disease that targets citrus found in Santa Paula, state order quarantine, Marketplace, October. Available at https://www.vcstar.com/story/news/local/2023/10/05/citrus-killing-disease-huanglongbing-hlb-santa-paula-california/71065314007/

Muth MK, Sweitzer M, Brown D, Capogrossi K, Karns S, Levin D, Okrent A, Siegel P and Zhen C (2016) Understanding IRI household-based and store-based scanner data, *TB–1942*, U.S. Department of Agriculture, Economic Research Service.

Okrent AM and Alston JM (2012) The demand for disaggregated food-away-from-home and food-at-home products in the United States, ERR-139, U.S. Department of Agriculture, Economic Research Service.

Park J, Holcomb R, Raper K and Capps O Jr. (1996) A demand system analysis of food commodities by U.S. households segmented by income. *American Journal of Agricultural Economics* **78**(2), 290–300.

Pollak RA and Wales TJ (1981) Demographic variables in demand analysis. *Econometrica* **49**(6), 1533–1551.

Rosen P (2023) Orange juice has never been this expensive, Business Insider, July 24. Link: Orange Crop Outlook for Brazil - Citrus Industry Magazine.

Texas Citrus Pest and Disease Management Corporation (2022) Link: Citrus Greening - Citrus Alert.

Thakuria D, Chaliha C, Dutta P, Sinha S, Uzir P, Sinh S, Hazarika S, Sahoo L, Kharbikar L and Singh D (2023) Citrus Huanglongbing (HLB): diagnostic and management options. *Physiological and Molecular Plant Pathology* **125**(1-12). https://doi.org/10.1016/j.pmpp.2023.102016

Tichenor N and Conrad Z (2015) Inter- and independent effects of region and race/ethnicity on variety of fruit and vegetable consumption in the USA: 2011 Behavioral Risk Factor Surveillance System (BRFSS). *Public Health Nutrition* **19**(1), 104–113.

University of Florida Citrus Research and Education Center (2022a) Link: Citrus Greening (Huanglongbing) - Citrus Research and Education Center - University of Florida, Institute of Food and Agricultural Sciences - UF/IFAS (ufl.edu).

University of Florida Citrus Research and Education Center (2022b) Link: University of Florida/IFAS awarded over $16 million in research grants to fight citrus disease - News (ufl.edu).

University of California, Division of Agriculture and Natural Resources (2022) Link: ACP/HLB Distribution and Management - Asian Citrus Psyllid Distribution and Management (ucanr.edu).

USDA (2022) Animal and Plant Health Inspection Service 2023 Explanatory Notes. Link USDA APHIS Explanatory Notes.

USDA APHIS (2022a) Pests and Diseases. Link: USDA APHIS | Pests and Diseases.

USDA APHIS (2022b) Pests and Diseases. Link: USDA APHIS | Citrus Greening.

USDA Economic Research Service (ERS) (2023) Link: USDA ERS - Food Availability (Per Capita) Data System.

USDA ERS (2022a) Link: USDA ERS - Food Consumption and Nutrient Intakes.

USDA ERS (2022b) Link: USDA ERS - Fruit and Tree Nuts Data.

USDA FAS (2022a) Citrus: Word markets and trade. Link: citrus.pdf (cornell.edu).

USDA, FAS (2022b) Citrus annual. Link: DownloadReportByFileName (usda.gov).
USDA, NASS (2022) Link: Citrus Fruits 2022 Summary 09/07/2022 (usda.gov).
USDA, NIFA (2021) NIFA Invests Nearly $11M to Combat and Prevent Citrus Greening Disease | National Institute of Food and Agriculture (usda.gov).
U.S. Department of Health and Human Services, Food and Drug Administration (2023) Link: Grapefruit Juice and Some Drugs Don't Mix.
U.S. Department of Labor, Bureau of Labor Statistics (2023) Link: Consumer Price Index (CPI) Databases.
Wales TJ and Woodland AD (1983) Estimation of consumer demand systems with binding non-negativity constraints. *Journal of Econometrics* **21**, 263–285.
You Z, Huang C and Epperson J (1997) Demand elasticities for fresh vegetables in the United States. *Journal of International Food and Agribusiness Marketing* **9**(2), 57–71.
Zapata SD, Peguero F, Sétamou M and Alabi OJ (2022) Economic implications of citrus greening disease management strategies. *Journal of Agricultural and Resource Economics* **47**(2), 300–323. doi: 10.22004/ag.econ.313310.

Appendix

Table A1. First stage parameter estimates, 2021

Variable	Parameter estimates	t-ratio
Intercept	1.28	11.48
Log (Age_head)	0.75	36.56
1/HHsize	−0.55	−11.01
College	0.16	17.81
White	−0.18	−9.80
Black	−0.06	−2.81
Asian	−0.03	−0.98
Single	−0.05	−1.81
Owner	0.03	2.39
Midwest	−0.13	−9.36
South	−0.13	−10.56
West	0.01	0.77
Age_5	0.30	14.15
Age_6_13	0.20	11.30
Log (Income)	0.18	15.87

https://doi.org/10.1017/age.2024.11 Published online by Cambridge University Press

Table A2. Second stage parameter estimates, 2021

	Expenditure share of									
	citrus fresh		citrus liquid		other fresh		other liquid		all other	
Variable	coeff.	st. er.	coeff.	st. er.	coeff.	st. er.	coeff.	st. er.	coeff.	st. er.
Demographic										
INTERCEPT	−1.944	0.070	−1.823	0.082	0.064	0.131	−0.752	0.074	5.454	0.185
AGE_HEAD	−0.057	0.012	0.007	0.015	−0.113	0.033	0.198	0.017	−0.034	0.041
HHSIZE	−0.050	0.028	−0.113	0.034	−0.263	0.078	0.291	0.042	0.135	0.098
COLLEGE	−0.023	0.005	−0.029	0.007	−0.017	0.015	0.028	0.008	0.042	0.019
WHITE	−0.022	0.012	−0.014	0.014	−0.040	0.031	0.140	0.017	−0.063	0.040
BLACK	0.051	0.014	0.039	0.017	0.033	0.038	−0.053	0.021	−0.070	0.048
ASIAN	−0.061	0.020	−0.029	0.019	−0.056	0.047	0.066	0.024	0.079	0.060
SINGLE	−0.054	0.017	−0.006	0.021	0.086	0.048	−0.061	0.025	0.034	0.060
OWNER	−0.025	0.006	−0.002	0.008	−0.005	0.018	0.047	0.009	−0.015	0.023
MIDWEST	0.038	0.008	0.021	0.010	0.001	0.023	−0.025	0.012	−0.034	0.029
SOUTH	0.018	0.008	0.021	0.009	0.010	0.021	−0.015	0.011	−0.034	0.026
WEST	0.007	0.009	0.019	0.010	0.002	0.024	−0.089	0.012	0.061	0.030
Total expenditure	0.516	0.012	0.490	0.014	−0.025	0.011	0.265	0.009	−1.245	0.023
Price of										
citrus fresh	−0.291	0.042								
citrus liquid	−0.467	0.027	−0.254	0.045						
other fresh	−0.006	0.022	−0.176	0.027	−0.126	0.044				
other liquid	−0.295	0.021	−0.096	0.021	−0.088	0.021	−0.508	0.022		
all others	1.058	0.059	0.993	0.062	0.143	0.060	−0.029	0.043	−2.166	0.113
Cholesky matrix of error term										
citrus fresh	0.663	0.002								
citrus liquid	−0.103	0.008	0.923	0.004						
other fresh	−0.173	0.009	−0.510	0.007	0.979	0.004				
other liquid	−0.225	0.011	−0.189	0.010	−0.665	0.007	0.778	0.004		
all others	−0.226	0.016	−0.340	0.015	0.251	0.014	0.048	0.017	0.267	0.031
quadratic parameter (λ)	−0.015	0.001	−0.012	0.001	0.006	0.001	−0.011	0.000	0.032	0.001

Cite this article: Dong, D., H. Stewart, A. T. Byrne, and M. Saavoss. 2024. "Citrus greening, retail fruit prices, and household welfare: A demand system approach." *Agricultural and Resource Economics Review*. https://doi.org/10.1017/age.2024.11