The Effects of Farm Commodity and Retail Food Policies on Obesity and Economic Welfare in the United States

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Many commentators claim that farm subsidies have contributed significantly to the "obesity epidemic" by making fattening foods relatively cheap and abundant and, symmetrically, that taxing "unhealthy" commodities or subsidizing "healthy" commodities would contribute to reducing obesity rates. In this article we use an equilibrium displacement model to estimate and compare the economic welfare effects from a range of hypothetical farm commodity and retail food policies as alternative mechanisms for encouraging consumption of healthy food or discouraging consumption of unhealthy food, or both. We find that, compared with retail taxes on fat, sugar, or all food, or subsidies on fruits and vegetables at the farm or retail levels, a tax on calories would be the most efficient obesity policy. A tax on calories would have the lowest deadweight loss per pound of fat reduction in average adult weight, and would yield a net social gain once the impact on public health care expenditures is considered.

Key words: Fat Taxes, Food Policy, Market Model, Obesity, Welfare.

JEL Codes: Q18, I18, H2.

Obesity is an escalating, worldwide problem that has received much attention recently, particularly in the United States. In less than thirty years, the prevalence of obese Americans has more than doubled (Flegal et al. 2002); in 1960–62, 13.4% of U.S. adults were obese, and by 2003–04, 32.2% were obese. This upward trend in the adult obesity rate has received a lot of press, with public health advocates demanding immediate action to reduce obesity rates. Indeed, First Lady Michelle Obama launched the 'Let's Move' campaign to address childhood obesity, so children will reach adulthood at a healthy weight (White House Task Force on Childhood Obesity 2010).

Obesity has become a public health issue because the consequences of obesity in terms of higher risk of morbidity and mortality for an individual translate into increased medical care costs, not only for the individual but also for society, and these costs are both large and growing. Finkelstein et al. (2009) estimated that 37% of the rise in inflation-adjusted per capita health care expenditures between 1998 and 2006 was attributable to increases in the proportion of Americans who were obese. Indeed, the increased prevalence of obesity was found to be responsible for almost $40 billion of increased medical spending between 1998 and 2006. Across all insured individuals, in 2006 per capita medical spending for the obese was $1,429 (roughly 42%) higher than for someone of normal weight, and more than half of the expenditures attributable to obesity were financed by Medicare and Medicaid.

The recent upward trend in the adult obesity rate is attributable to an energy imbalance, whereby calories consumed are greater than calories expended, given a genetic predisposition. Arguably, the genetic composition of the United States has not

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This project was supported by the National Research Initiative of the Cooperative State Research, Education and Extension Service, USDA, Grant # 2006-55215-16720. We also gratefully acknowledge financial and indirect support from the University of California Agricultural Issues Center and the Giannini Foundation of Agricultural Economics. Joanna Parks provided substantial assistance with some calculations, and two anonymous reviewers and participants at several workshops and conferences provided helpful comments and suggestions. We gratefully acknowledge these helpful contributions to this work.

Amer. J. Agr. Econ. 94(3): 611–646; doi: 10.1093/ajae/aar138
Received 1 November 2011; published online February 22, 2012

Published by Oxford University Press on behalf of the Agricultural and Applied Economics Association 2012.

changed significantly in the past 20 years; thus, increases in the rate of obesity imply that many individuals have increased their consumption of calories or decreased their physical activity, or both. Over the past two decades, median body weight increased 10–12 lbs for adult men and women. This rate of gain required a net calorie imbalance of 100 to 150 calories per day (Cutler, Glaeser, and Shapiro 2003). Because the daily energy imbalance is relatively small, many economic factors such as price and income changes, coupled with changes in individual preferences, could have contributed to the observed gain in body weight.

Policy makers have discussed a variety of policies to address obesity in the United States. Regulatory and fiscal instruments have been suggested as ways to change the eating habits of individuals: for instance, taxing foods with high fat or high sugar content, or subsidizing healthier foods such as fresh fruits and vegetables. However, economists disagree about the extent to which changes in food prices have contributed to the increased rate of obesity in the United States. Some studies suggest that taxation or subsidization of certain foods would be effective as a means of reducing average body weight in the United States (O'Donoghue and Rabin 2006; Cash, Sunding, and Zilberman 2005). A tax on foods that are energy dense and fattening (e.g. soda and chips) would make fattening foods more expensive relative to non-fattening foods such that consumers would substitute away from the consumption of fattening foods and towards consumption of non-fattening foods. Others argue that such pricing policies would have little effect on food consumption, and hence obesity (Schroeter, Lusk, and Tyner 2007; Kuchler, Tegene and Harris 2004; Chouinard et al. 2007; Gelbach, Klick, and Strattman 2007) and would be regressive, falling disproportionately heavily on the poor (e.g., Chouinard et al. 2007).

Related to the issue of whether food prices have been a major contributor to obesity in the United States is the question of whether agricultural policies make farm commodities cheaper and more abundant, especially those that are primary ingredients in fattening foods. The idea that farm subsidies have contributed significantly to the problem of obesity in the United States has been reported frequently in the press, and has assumed the character of a stylized fact. It is conceptually possible that farm policies have contributed to lower relative prices and increased consumption of fattening foods by making certain farm commodities more abundant and therefore cheaper. However, several economic studies have found these effects to be small or nonexistent (Alston, Sumner, and Vosti 2006, Alston, Sumner, and Vosti 2008, Beghin and Jensen 2008, Miller and Coble 2007, Schmidhuber 2004, Senauer and Gemma 2006).

To date, most evaluations of food taxes and subsidies as obesity policies have primarily focused on consumer responses, largely ignoring the potential role that producers play in food production and consumption. In this paper we model and quantify the potential impacts on food consumption, body weight, and social welfare that would result from subsidies and taxes on food products, or on farm commodities used to produce food. To do so, we develop a framework that is a generalization of models of commodity-retail product price transmission discussed in the marketing margins literature. Based on this general framework, we also establish formulas for approximating policy-induced changes in social welfare that do not rely on a particular choice of functional form for the consumer expenditure function or for the producer profit function. We apply these methods to simulate various policies and their impacts on prices, consumption, and welfare. To do this, we use new estimates of demand elasticities for food and other goods, estimated specifically with this application in mind, combined with estimates of commodity supply elasticities from the literature, along with detailed data on farm-to-retail marketing costs and the nutrient content of different foods.

A Model of *N* Inter-related Food Products and *L* Inter-related Commodities

To determine the implications of agricultural policies for obesity and its economic consequences, we develop an equilibrium displacement model that can be used to examine the transmission of policy-induced changes in commodity prices to changes in consumption and prices of food products. Gardner (1975) developed a one-output, two-input model of a competitive industry to analyze how the retail-farm price ratio responds to shifts in the supply of farm commodities or marketing inputs, or in the demand for retail products. Gardner derived formulas for elasticities of price transmission that nest the fixed proportions model of Tomek and Robinson (2003) as a special case. Wohlgenant (1989) and Wohlgenant and

Haidacher (1989) developed a different one-output, two-input model for which they did not assume constant returns to scale at the industry level. For each of eight food products, these authors estimated the respective elasticities of price transmission between the retail price and the prices of a corresponding farm commodity and a composite marketing input.

The linkages between markets for farm commodities and retail products are generally modeled assuming that one farm commodity and one or more marketing factors are inputs into the production of a particular food at home (FAH) (i.e. food purchased at a retail outlet and prepared at home). For example, the farm commodity beef is the primary ingredient for the retail food product beef. However, food away from home (FAFH) (e.g. food purchased at restaurants) and combination FAH products (e.g. soups, frozen dinners) incorporate multiple farm commodities. Under the assumption of fixed proportions, the price transmission between farm commodities and both combination FAH products and FAFH would certainly be less than the price transmission between farm commodities and non-combination FAH products, because the farm commodity cost represents a smaller share of the retail value of FAH and combination food products. FAFH and combination foods now constitute more than half of personal consumption expenditures on food–41 and 14%, respectively in 2009 (U.S. Department of Commerce, Bureau of Economic Analysis 2010), and the majority of average daily calories consumed are from these two categories of food–33% and 18%, respectively, in 2005–06 (Centers for Disease Control and Prevention, National Center for Health Statistics 2010). Consequently, it is important to include these categories of food when analyzing food policies and obesity.

Here we extend a system comprising one output product with L inputs, as presented by Wohlgenant (1982), to N output products with L-1 farm commodities used as inputs, along with one composite marketing input.[1] The market equilibrium for this system can be expressed in terms of N demand equations for food products, N total cost equations for food product supply, L supply equations for input commodities, and $L \times N$ equations for competitive market clearing:

$$(1) \quad Q^n = \mathrm{Q}^n(\mathbf{P}, A^n), \forall n = 1, \ldots, N,$$

$$(2) \quad C^n = \mathrm{c}^n(\mathbf{W})Q^n, \forall n = 1, \ldots, N,$$

$$(3) \quad X_l^n = \left(\partial \mathrm{c}^n(\mathbf{W})/\partial W_l\right) Q^n = \mathrm{g}_l^n(\mathbf{W})Q^n, \quad \forall n = 1, \ldots, N; \forall l = 1, \ldots, L,$$

$$(4) \quad X_l = \mathrm{f}_l(\mathbf{W}, B_l), \forall l = 1, \ldots, L.$$

The superscripts on variables and functions denote food products, while the subscripts denote farm commodities and the composite marketing input. Equation (1) represents the demand for the nth retail food product in which the quantity demanded, Q^n, is a function of an $N \times 1$ vector of retail prices, $\mathbf{P}$, and an exogenous demand shifter, A^n, which subsumes the effects of changes in total consumer expenditures and other exogenous shifters on retail demand. In equation (2), the technology for the industry producing good n is expressed as a total cost function in which the total cost of producing the nth retail product C^n is a function of an $L \times 1$ vector of prices of farm commodities and the marketing input, $\mathbf{W}$, and the quantity of the product, Q^n. Under the assumption of constant returns to scale at the industry level, the average cost per unit of product, n, is equivalent to its marginal cost (i.e. $C^n/Q^n = \mathrm{c}^n(\mathbf{W})$), and, under the further assumption of competitive market equilibrium with no price distortions, marginal cost and average cost are equal to the retail price, P^n:

$$(5) \quad P^n = \mathrm{c}^n(\mathbf{W}), \forall n = 1, \ldots, N.$$

The Hicksian demand for commodity l by industry n in equation (3) is derived by applying Shephard's lemma to the total cost function in (2). The $L \times N$ Hicksian demand equations can be reduced to L equations because total demand for commodity l, X_l, is the sum of the Hicksian demands for commodity l across all retail industries, that is,

$$(6) \quad X_l = \sum_{n=1}^{N} \mathrm{g}_l^n(\mathbf{W})Q^n, \forall l = 1, \ldots, L.$$

Equation (4) is the supply function for commodity l, which is a function of all of the commodity prices and an exogenous supply shifter, B_l.

Totally differentiating equations (1), (4), (5), and (6), and expressing these equations in relative change terms (i.e. using $dX_i/X_i = \mathrm{E}X_i$)

[1] For the rest of this analysis, "commodities" will include farm commodities and the composite marketing input.

yields:

$$(7)\quad \mathrm{E}Q^n = \sum_{k=1}^{N} \eta^{nk}\, \mathrm{E}P^k + \alpha^n, \quad \forall n = 1, \ldots, N,$$

$$(8)\quad \mathrm{E}P^n = \sum_{l=1}^{L} \frac{\partial c^n(\mathbf{W})}{\partial W_l} \frac{W_l}{P^n}\, \mathrm{E}W_l, \quad \forall n = 1, \ldots, N,$$

$$(9)\quad \mathrm{E}X_l = \sum_{n=1}^{N} SC_l^n \sum_{m=1}^{L} \left(\eta_{lm}^{n*}\, \mathrm{E}W_m + \mathrm{E}Q^n\right), \forall l = 1, \ldots, L,$$

$$(10)\quad \mathrm{E}X_l = \sum_{j=1}^{L} \varepsilon_{lj}\, \mathrm{E}W_j + \beta_l, \quad \forall l = 1, \ldots, L,$$

where

$$(11)\quad \eta^{nk} = \frac{\partial\, Q^n(\mathbf{P}, A^n)}{\partial P^k} \frac{P^k}{Q^n}$$

is the Marshallian elasticity of demand for retail product n with respect to retail price k,

$$(12)\quad SC_l^n = \frac{X_l^n W_l}{X_l W_l}$$

is the share of the total cost of commodity l across all industries used by retail product n (farm-commodity share),

$$(13)\quad \eta_{lm}^{n*} = \left(\frac{\partial\, g_l^n(\mathbf{W}) Q^n}{\partial W_m}\right) \frac{W_m}{X_l^n}$$

is the Hicksian elasticity of demand for commodity l in industry n with respect to commodity price m,

$$(14)\quad \varepsilon_{lj} = \frac{\partial\, f_l(\mathbf{W}, B_l)}{\partial W_j} \frac{W_j}{X_l}$$

is the elasticity of supply of commodity l with respect to commodity price j,

$$(15)\quad \alpha^n = \frac{\partial\, Q^n(\mathbf{P}, A^n)}{\partial A^n} \frac{A^n}{Q^n}\, \mathrm{E}A^n$$

is the proportional shift of demand for retail product n in the quantity direction, and

$$(16)\quad \beta_l = \frac{\partial\, f_l(W_l, B_l)}{\partial B_l} \frac{B_l}{X_l}\, \mathrm{E}B_l$$

is the proportional shift of supply of commodity l in the quantity direction.

Several simplifications can be made to the system. First, we know that $\partial c^n(\cdot)/\partial W_l = X_l^n/Q^n$, so equation (8) can be rewritten as:

$$(17)\quad \mathrm{E}P^n = \sum_{l=1}^{L} SR_l^n\, \mathrm{E}W_l, \forall n = 1, .., N,$$

where the share of total cost for retail product n attributable to commodity l (farm-product share) is:

$$(18)\quad SR_l^n = X_l^n W_l / P^n Q^n.$$

Second, the share-weighted Hicksian elasticity of demand for commodity l with respect to the price of commodity m is:

$$(19)\quad \eta_{lm}^{*} = \sum_{n=1}^{N} SC_l^n \eta_{lm}^{n*}.$$

Finally, equation (9) can be rewritten using (19):

$$(20)\quad \mathrm{E}X_l = \sum_{m=1}^{L} \eta_{lm}^{*}\, \mathrm{E}W_m + \sum_{n=1}^{N} SC_l^n \mathrm{E}Q^n, \forall l = 1, \ldots, L.$$

This system can be modified to accommodate policy shocks such as the introduction of taxes and subsidies on food products or taxes and subsidies on farm commodities. The subsidy and taxation policies cause wedges between consumer (or buyer) and producer (or seller) prices of retail products or commodities. Let t^n be the tax rate on food product n, and $P^{D,n}$ and $P^{S,n}$ be the consumer and producer prices of retail product n, respectively, such that:

$$(21)\quad P^{D,n} = (1 + t^n) P^{S,n}.$$

The introduction of t^n implies that the total differential of (21) expressed in terms of proportionate changes is:

$$(22)\quad \mathrm{E}P^{D,n} = t^n + \mathrm{E}P^{S,n}.$$

Substituting (22) into (7) yields:

$$(23)\quad \mathrm{E}Q^n = \sum_{k=1}^{N} \eta^{nk}\, \mathrm{E}P^{Sk}, + \sum_{k=1}^{N} \eta^{nk} t^k + \alpha^n.$$

Likewise, the proportionate change in the seller price of commodity l, $\mathrm{E}W_{S,l}$, can be written as the sum of its subsidy rate, s_l, and the proportionate change in its buyer price:

$$(24)\quad EW_{S,l} = s_l + EW_{D,l}.$$

Substituting (24) into (10) yields:

$$(25)\quad EX_l = \sum_{j=1}^{L} \varepsilon_{lj}\, EW_{D,l} + \sum_{j=1}^{L} \varepsilon_{lj} s_l + \beta_l.$$

To simplify the notation, we present equations (17), (20), (23) and (25) in matrix notation. Letting $\mathbf{EQ}$, and $\mathbf{EP}^S$ be $N \times 1$ vectors of proportionate changes in quantities and producer prices of retail products, respectively, and $\mathbf{EX}$, and $\mathbf{EW}_D$ be $L \times 1$ vectors of proportionate changes in quantities and buyer prices of commodities, respectively, the system is:

$$(26)\quad \begin{bmatrix} \mathbf{I}^N & -\boldsymbol{\eta}^N & \mathbf{0} & \mathbf{0} \\ \mathbf{0}^N & \mathbf{I}^N & \mathbf{0} & -\mathbf{SR} \\ -\mathbf{SC} & \mathbf{0}^{\mathrm{T}} & \mathbf{I}_L & -\boldsymbol{\eta}_L^* \\ \mathbf{0}^{\mathrm{T}} & \mathbf{0}^{\mathrm{T}} & \mathbf{I}_L & -\boldsymbol{\varepsilon}_L \end{bmatrix} \begin{bmatrix} \mathbf{EQ} \\ \mathbf{EP}^S \\ \mathbf{EX} \\ \mathbf{EW}_D \end{bmatrix} = \begin{bmatrix} \boldsymbol{\alpha} + \boldsymbol{\eta}^N \mathbf{t}^N \\ \mathbf{0} \\ \mathbf{0} \\ \boldsymbol{\beta} + \boldsymbol{\varepsilon}_L \mathbf{s}_L \end{bmatrix},$$

where $\mathbf{I}^N$ and $\mathbf{I}_L$ are $N \times N$ and $L \times L$ identity matrices, $\mathbf{0}^N$ and $\mathbf{0}$ are $N \times N$ and $N \times L$ matrices of all zeros, $\boldsymbol{\eta}^N$ is an $N \times N$ matrix of Marshallian elasticities of demand for retail products (equation(11)), $\boldsymbol{\eta}_L^*$ is an $L \times L$ matrix of Hicksian elasticities of demand for commodities (equation (19)), $\mathbf{SR}$ is an $N \times L$ matrix of farm-product shares (equation (18)), $\mathbf{SC}$ is an $L \times N$ matrix of farm-commodity shares (equation(12)), $\boldsymbol{\varepsilon}_L$ is an $L \times L$ matrix of elasticities of supply of commodities (equation(14)), and $\boldsymbol{\alpha} + \boldsymbol{\eta}^N \mathbf{t}^N$ and $\boldsymbol{\beta} + \boldsymbol{\varepsilon}_L \mathbf{s}_L$ are $N \times 1$ and $L \times 1$ vectors of exogenous factors affecting the demand for retail products and the supply of commodities, respectively. Using matrix block inversion, the solutions for $\mathbf{EQ}$, $\mathbf{EP}^S$, $\mathbf{EX}$ and $\mathbf{EW}_D$ are:

$$(27)\quad \begin{bmatrix} \mathbf{EQ} \\ \mathbf{EP}^S \\ \mathbf{EX} \\ \mathbf{EW}_D \end{bmatrix} = \begin{bmatrix} \mathbf{I}^N - \boldsymbol{\eta}^N \mathbf{SR} \mathbf{f}^{-1} \mathbf{SC} & \boldsymbol{\eta}^N \mathbf{SR} \mathbf{f}^{-1} \\ -\mathbf{SR} \mathbf{f}^{-1} \mathbf{SC} & \mathbf{SR} \mathbf{f}^{-1} \\ \left(\mathbf{I}_L - (\boldsymbol{\eta}_L^* + \mathbf{SC} \boldsymbol{\eta}^N \mathbf{SR}) \mathbf{f}^{-1}\right) \mathbf{SC} & \left(\boldsymbol{\eta}_L^* + \mathbf{SC} \boldsymbol{\eta}^N \mathbf{SR}\right) \mathbf{f}^{-1} \\ -\mathbf{f}^{-1} \mathbf{SC} & \mathbf{f}^{-1} \end{bmatrix} \times \begin{bmatrix} \boldsymbol{\alpha} + \boldsymbol{\eta}^N \mathbf{t}^N \\ \boldsymbol{\beta} + \boldsymbol{\varepsilon}_L \mathbf{s}_L \end{bmatrix},$$

where $\mathbf{f}^{-1} = (-\boldsymbol{\varepsilon}_L + \boldsymbol{\eta}_L^* + \mathbf{SC} \boldsymbol{\eta}^N \mathbf{SR})^{-1}$. The vectors of proportionate changes in consumer prices of retail products and seller prices of commodities, $\mathbf{EP}^D$ and $\mathbf{EW}_S$, respectively, can be recovered using (22) and (24).

Simplifying assumptions can be used to reduce the general model to a more manageable form, such as (a) exogenous commodity prices ($\varepsilon_{ll} = \infty$), (b) exogenous commodity quantities ($\varepsilon_{ll} = 0$), or (c) fixed input proportions ($\sigma_{lj} = 0$). Under the assumption of exogenous commodity prices, equation (25) becomes:

$$(28)\quad -d \ln W_l = \bar{\beta}_l + s_l, \forall l = 1, \ldots, L,$$

where $\bar{\beta}_l$ is a proportionate shift in supply of commodity l in the price direction. Under this assumption, the solution in (27) reduces to the first column in table 1. Wohlgenant and Haidacher (1989) and Wohlgenant (1989) assumed that farm commodity supply is predetermined with respect to the farm commodity price in the current period, which implies that $\varepsilon_{lj} = 0, \forall j, l = 1, \ldots, L$, such that (25) becomes:

$$(29)\quad EX_l = \beta_l, \forall l = 1, \ldots, L.$$

This implies that the general model reduces to the second column in table 1. Lastly, under an assumption of fixed proportions, the Hicksian elasticity of demand between two factor inputs l and j in output n is zero (i.e. $\eta_{lj}^{n*} = 0$, $\forall l, j = 1, \ldots, L, \forall n = 1, \ldots, N$).[2] Hence, the solution with fixed input proportions is that from the general model with $\boldsymbol{\eta}_L^* = \mathbf{0}_L$, or the last column in table 1.

Measures of Changes in Social Welfare

Based on the general price transmission model, we formulate equations for estimating the

[2] To show the implications of this assumption for the general model, note that the elasticity of substitution can be written as: $\sigma_{ij}^n = \left(\frac{\partial^2 C^n(\mathbf{W}, Q^n)}{\partial P^i \partial P^j}\right) C^n(\mathbf{W}, Q^n) / \left(\frac{\partial C^n(\mathbf{W}, Q^n)}{\partial P^i}\right)\left(\frac{\partial C^n(\mathbf{W}, Q^n)}{\partial P^j}\right)$ (Sato and Koizumi 1975). Conveniently, this definition of the elasticity of substitution relates directly to the Hicksian elasticity of demand for the inputs, $\eta_{lj}^{n*} = \sigma_{lj}^n SR_l^n, \forall l, j = 1, \ldots, L, \forall n = 1, \ldots, N$. Substituting this into (18), the farm-product-share-weighted Hicksian elasticity of demand for commodity l with respect to price of commodity m becomes $\eta_{lm}^* = \sum_{n=1}^{N} SC_l^n \sigma_{lm}^{n*} SR_l^n$.

Table 1. Price and Quantity Effects of Taxes and Subsidies on Retail Products and Farm Commodities for Nested Cases of the General Model

	Perfectly Elastic Commodity Supply $\varepsilon_{ll} = \infty$	Perfectly Inelastic Commodity Supply $\varepsilon_{ll} = 0$	Fixed Factor Proportions $\sigma_{lj} = 0$
EQ	$\bar{\mathbf{X}}^{\alpha} - \boldsymbol{\eta}^{N}\mathbf{SR}\bar{\mathbf{X}}_{\beta}$	$(\mathbf{I}^{N} - \boldsymbol{\eta}^{N}\mathbf{SR}\tilde{\mathbf{f}}^{-1}\mathbf{SC})\tilde{\mathbf{X}}^{\alpha}$ $+\boldsymbol{\eta}^{N}\mathbf{SR}\tilde{\mathbf{f}}^{-1}\tilde{\mathbf{X}}_{\beta}$	$(\mathbf{I}^{N} - \boldsymbol{\eta}^{N}\mathbf{SR}\hat{\mathbf{f}}^{-1}\mathbf{SC})\hat{\mathbf{X}}^{\alpha}$ $+\boldsymbol{\eta}^{N}\mathbf{SR}\hat{\mathbf{f}}^{-1}\hat{\mathbf{X}}_{\beta}$
EP^{S}	$-\mathbf{SRX}_{\beta}$	$\mathbf{SR}\tilde{\mathbf{f}}^{-1}\mathbf{SC}\tilde{\mathbf{X}}^{\alpha} + \mathbf{SR}\tilde{\mathbf{f}}^{-1}\tilde{\mathbf{X}}_{\beta}$	$\mathbf{SR}\hat{\mathbf{f}}^{-1}\mathbf{SC}\hat{\mathbf{X}}^{\alpha} + \mathbf{SR}\hat{\mathbf{f}}^{-1}\hat{\mathbf{X}}_{\beta}$
EX	$\mathbf{SC}\bar{\mathbf{X}}^{\alpha}$ $-(\mathbf{SC}\boldsymbol{\eta}^{N}\mathbf{SR} + \boldsymbol{\eta}_{L}^{*})\bar{\mathbf{X}}_{\beta}$	$\tilde{\mathbf{X}}_{\beta}$	$(\mathbf{I}_{L} - \mathbf{SC}\boldsymbol{\eta}^{N}\mathbf{SR}\hat{\mathbf{f}}^{-1})\mathbf{SC}\hat{\mathbf{X}}^{\alpha}$ $+\mathbf{SC}\boldsymbol{\eta}^{N}\mathbf{SR}\hat{\mathbf{f}}^{-1}\hat{\mathbf{X}}_{\beta}$
EW$_{D}$	$-\bar{\mathbf{X}}_{\beta}$	$\tilde{\mathbf{f}}^{-1}\mathbf{SC}\tilde{\mathbf{X}}^{\alpha} + \tilde{\mathbf{f}}^{-1}\tilde{\mathbf{X}}$	$\hat{\mathbf{f}}^{-1}\mathbf{SC}\hat{\mathbf{X}}^{\alpha} + \hat{\mathbf{f}}^{-1}\hat{\mathbf{X}}_{\beta}$

Notes: $\bar{\mathbf{X}}^{\alpha} = \boldsymbol{\alpha} + \boldsymbol{\eta}^{N}\mathbf{t}^{N}, \bar{\mathbf{X}}_{\beta} = \bar{\boldsymbol{\beta}} + \mathbf{s}_{L}$
$\tilde{\mathbf{X}}^{\alpha} = \boldsymbol{\alpha} + \boldsymbol{\eta}^{N}\mathbf{t}^{N}, \tilde{\mathbf{X}}_{\beta} = \boldsymbol{\beta}, \tilde{\mathbf{f}}^{-1} = (\boldsymbol{\eta}_{L}^{*} + \mathbf{SC}\boldsymbol{\eta}^{N}\mathbf{SR})^{-1}$
$\hat{\mathbf{X}}^{\alpha} = \boldsymbol{\alpha} + \boldsymbol{\eta}^{N}\mathbf{t}^{N}, \hat{\mathbf{X}}_{\beta} = \boldsymbol{\beta} + \boldsymbol{\varepsilon}_{L}\mathbf{s}_{L}, \hat{\mathbf{f}}^{-1} = (-\boldsymbol{\varepsilon}_{L} + \mathbf{SC}\boldsymbol{\eta}^{N}\mathbf{SR})^{-1}$

change in social welfare from a subsidy or tax policy. Changes in social welfare are measured as the sum of benefits (costs) that accrue to consumers, producers, and taxpayers from a policy shock. Measures of compensating variation (CV) and changes in profit and taxpayer revenue (expenditure) are used to represent these benefits (costs). This measure of social welfare is then adjusted to account for externalities that are borne by taxpayers who bear some of the costs for the health care services of obese individuals who use government-funded insurance.

Following Martin and Alston (1992, 1993) and Just, Hueth and Schmitz (2004), we define social welfare (SW) as:

$$(30) \quad SW = \sum_{n=1}^{N}[\pi(P^{n}, \mathbf{W})] + \sum_{l=1}^{L}[\pi(W_{l})] + \mathrm{g}(\mathbf{P}, \mathbf{W}) - \sum_{i=1}^{I}\mathrm{e}(\mathbf{P}, u_{i}),$$

where $\mathrm{e}(\mathbf{P}, u_i)$ is the minimum expenditure necessary to obtain a given level of utility, u_i for individual consumer i at product prices, $\mathbf{P}$; $\pi(P^n, \mathbf{W})$ is profit for retail product producer n, where $\mathbf{W}$ is an $L \times 1$ vector of commodity prices; $\pi(W_l)$ is profit for commodity producer l; and $\mathrm{g}(\mathbf{P}, \mathbf{W})$ is change in government revenue generated by the introduction of the policy being analyzed.[3] A compensating variation measure of the change in social welfare for a representative consumer, retail product producer, and commodity producer is:

$$(31) \quad \Delta SW = [\pi(\mathbf{P}^{(1)}, \mathbf{W}^{(1)}) - \pi(\mathbf{P}^{(0)}, \mathbf{W}^{(0)})] + [\pi(\mathbf{W}^{(1)}) - \pi(\mathbf{W}^{(0)})] + [\mathrm{g}(\mathbf{P}^{(1)}, \mathbf{W}^{(1)}) - \mathrm{g}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)})] - [\mathrm{e}(\mathbf{P}^{(1)}, u^{(0)}) - \mathrm{e}(\mathbf{P}^{(0)}, u^{(0)})],$$

where the last term in square brackets is the amount of income that must be taken away from consumers after prices change from $\mathbf{P}^{(0)}$ to $\mathbf{P}^{(1)}$ to restore the consumer's original utility at $u^{(0)}$ (i.e. compensating variation, CV).[4] Martin and Alston (1992) demonstrated how a second-order Taylor series expansion of (30) around $(\mathbf{P}^{(0)}, \mathbf{W}^{(0)})$, holding utility constant at $u^{(0)}$, can be used to approximate (31) without specifying functional forms for the consumer expenditure and profit functions:

$$(32) \quad SW(\mathbf{P}, \mathbf{W}, u^{(0)}) \approx SW(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) + \boldsymbol{\Delta}^{\mathrm{T}}\nabla\, \mathrm{SW}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) + 0.5\boldsymbol{\Delta}^{\mathrm{T}}\nabla^{2}\, \mathrm{SW}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)})\boldsymbol{\Delta},$$

[3] This treatment assumes that one dollar of government revenue is worth one dollar. It would be a straightforward extension to allow for the marginal social opportunity cost of government revenue to be greater than one dollar, as is implied by the fact that general taxation measures involve deadweight losses (Alston and Hurd 1990). Doing so would shift the balance of the equation in favor of the tax policies.

[4] Since retail producers are assumed to make zero profit (i.e. equation 2),

$$[\pi(\mathbf{P}^{(1)}, \mathbf{W}^{(1)}) - \pi(\mathbf{P}^{(0)}, \mathbf{W}^{(0)})] = 0.$$

where ∇ and ∇^2 denote the gradient and Hessian of the social welfare function, respectively, the T superscript denotes the transpose of a matrix, and $\mathbf{\Delta}^{\mathrm{T}} = [\mathbf{\Delta P}^D \quad \mathbf{\Delta P}^S \quad \mathbf{\Delta W}_D \quad \mathbf{\Delta W}_S]$, is a $2(N+1)$ vector of changes in producer and consumer prices of products and commodities, respectively.

Evaluating (32) at $(\mathbf{P}^{D(1)}, \mathbf{P}^{S(1)}, \mathbf{W}_D^{(1)}, \mathbf{W}_S^{(1)})$ and then subtracting $\mathrm{SW}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)})$ from both sides yields an approximation to the change in social welfare implied by a change in prices from $(\mathbf{P}^{(0)}, \mathbf{W}^{(0)})$ to $(\mathbf{P}^{(1)}, \mathbf{W}^{(1)})$ as would be implied by a policy simulation using the price transmission model:

$$(33) \quad \Delta SW = \mathrm{SW}(\mathbf{P}^{(1)}, \mathbf{W}^{(1)}, u^{(0)}) - \mathrm{SW}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) \approx \mathbf{\Delta}^{(1)\mathrm{T}} \nabla \mathrm{SW}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) + 0.5\mathbf{\Delta}^{(1)\mathrm{T}} \times \nabla^2 \mathrm{SW}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) \mathbf{\Delta}^{(1)},$$

where $\mathbf{\Delta}^{(1)\mathrm{T}} = [\mathbf{P}^{D(1)} - \mathbf{P}^{(0)} \quad \mathbf{P}^{S(1)} - \mathbf{P}^{(0)} \quad \mathbf{W}_D^{(1)} - \mathbf{W}^{(0)} \quad \mathbf{W}_S^{(1)} - \mathbf{W}^{(0)}]$.
The approximation in (33) reduces to:

$$
\begin{aligned}
(34) \quad \Delta SW \approx\ & (\mathbf{EW}_S)^{\mathrm{T}} \mathbf{D}_W \mathbf{X}^{(0)} \\
& + 0.5(\mathbf{EW}_S)^{\mathrm{T}} \mathbf{D}_{WX} \boldsymbol{\varepsilon}_L \mathbf{EW}_S && \text{(a)} \\
& - [(\mathbf{EP}^D)^{\mathrm{T}} \mathbf{D}^P \mathbf{Q}^{(0)} + 0.5(\mathbf{EP}^D)^{\mathrm{T}} && \text{(b)} \\
& \times \mathbf{D}^{PQ} (\boldsymbol{\eta}^N + \boldsymbol{\eta}^{N,M} \mathbf{w}^{\mathrm{T}}) \mathbf{EP}^D] && \text{(c)} \\
& + (\mathbf{t}^N)^{\mathrm{T}} \mathbf{D}_P \mathbf{Q} + (\mathbf{t}^N)^{\mathrm{T}} \mathbf{D}_{PQ} \mathbf{EQ} && \text{(d)} \\
& - (\mathbf{s}_L)^{\mathrm{T}} \mathbf{D}_W \mathbf{X} - (\mathbf{s}_L)^{\mathrm{T}} \mathbf{D}_{WX} \mathbf{EX} && \text{(e)}
\end{aligned}
$$

(see Technical Appendix).

In this equation the measure of social welfare change depends on the initial prices and quantities of food products and of commodities used as inputs to produce them, the elasticities of commodity supply and product demand, the exogenous rates of tax and subsidy, and the proportional changes in prices of commodities and products that would result from introducing those taxes and subsidies. The approximation of social welfare in (34) is graphically intuitive; note that line (a) and lines (b) and (c) in equation (34) are the change in profits across all commodity markets and the compensating variation across all retail product markets, respectively. Line (d) comprises the change in government revenue from introducing a set of retail taxes, and line (e) comprises the change in government revenue from introducing a set of commodity subsidies.

We augment the measures of change in social welfare to reflect changes in public health care expenditures related to changes in obesity status. To quantify the change in government health care expenditures associated with policy-induced changes in food consumption and obesity status, we use a multiplier estimated by Parks, Alston, and Okrent (2011) based on evidence regarding the relationship between health expenditures and body mass index (BMI), and knowledge of the distribution of the U.S. population by BMI.[5] This multiplier (e) measures the change in public health care expenditures for a one pound per person change in average adult body weight. Thus, the total change in public health care expenditures (H) is given by:

$$(35) \quad \Delta H = e\Delta\bar{B} = e\sum_{n=1}^{N}\left(Q^n \frac{\partial \bar{B}}{\partial Q^n}\right) \mathrm{E}Q^n,$$

where $\bar{B}$ is average adult body weight, $\partial\bar{B}/\partial Q^n$ is the marginal change in pounds of average body weight for a one-kilogram increase in the consumption of food n, which reflects both the caloric content of food and the translation of dietary calories into weight, and $\mathrm{E}Q^n$ is the proportional change in annual consumption of good n. The full measure of the annual change in social welfare from a policy shock that induces changes in public health care spending, is therefore:

$$(36) \quad \Delta SW^* = \Delta SW - e\bar{B}(\boldsymbol{\eta}^{BQ})^{\mathrm{T}} \mathbf{EQ},$$

where ΔSW is the annual change in social welfare defined in (34), $\boldsymbol{\eta}^{BQ}$ is an $N \times 1$ vector of elasticities of weight with respect to quantities consumed of different foods, and $\mathbf{EQ}$ is defined in (27) for the general model and in table 1 for the nested cases.

[5] BMI is defined as body weight (B) in kilograms divided by height (H) in meters squared. Much has been written documenting the weaknesses of BMI as a measure of obesity. For example, Parks, Smith, and Alston (2011) reviewed the relevant literature and evaluated BMI compared with alternatives. Nevertheless, BMI is widely used as an index of obesity, and consequently information about the relationship between obesity and health outcomes is often expressed as a relationship between BMI and health outcomes, such that it is reasonable to use BMI as we do in the present context.

Data

The data necessary to parameterize the model include (a) Marshallian elasticities of demand for food products; (b) farm-retail product shares (i.e. the cost of each individual farm commodity as a share of the value of each retail food product) and farm-commodity shares (i.e. the share of each commodity used in the production of each retail food product); (c) elasticities of supply of farm commodities and the composite marketing input; (d) elasticities of substitution between farm commodities and the composite marketing input (i.e., Hicksian elasticities of demand for commodities); (e) food-to-weight multipliers; and (f) weight-to-health-expenditure multipliers. In all of the simulations, we assumed fixed proportions technology in the food industry, such that all Hicksian elasticities of demand for commodities are zero (i.e., $\boldsymbol{\eta}_L^* = \mathbf{0}$).

First, to parameterize $\boldsymbol{\eta}^N$ we use elasticities of demand based on estimates taken from Okrent and Alston (2011) for eight FAH products (i.e. cereals and bakery products, red meat, poultry and eggs, seafood and fish, dairy, fruits and vegetables, other foods, and non-alcoholic beverages), a FAFH composite, and alcoholic beverages. The Marshallian elasticities of demand for these products evaluated at the sample means of the data are listed in table 2a.[6]

Predicted changes in quantities and the implied welfare measures based on the price transmission model are largely dependent on the estimates of elasticities of demand for food products. To gauge the sensitivity of our results to errors in estimation of the elasticities of demand for food products, we used Monte Carlo integration (Piggott 2003; Chalfant, Gray and White 1991). The elasticities of demand in table 2a are based on a vector of parameter estimates ($\hat{\gamma}$) with an associated covariance matrix ($\hat{\Sigma}$). We randomly drew parameters from a multivariate normal distribution with mean $\hat{\gamma}$ and covariance matrix $\hat{\Sigma}$. The elasticities of demand were re-estimated for each draw that satisfied curvature and monotonicity conditions; those estimates were used to solve the price transmission model and compute the implied changes in calorie consumption and body weight, holding all other parameters constant. The solutions were used to generate empirical posterior distributions for the effects of interest, and we report the means from the posterior distributions and standard deviations around those means. Table 2b includes the means of the elasticities from the empirical posterior distribution, which are generally similar to the corresponding point estimates in table 2a, and their standard deviations.

For the elasticities of supply of farm commodities ($\boldsymbol{\varepsilon}_L$), we examine two cases. First, we assume that commodity prices are exogenous. The assumption of exogenous commodity prices is implicitly an extreme assumption about the elasticities of supply. In this case, the elasticities of supply of the commodities are all effectively infinite, and the solutions to the general model collapse to the nested solutions in table 1. The assumption of exogenous prices may be extreme, but it has been applied widely in models of food policy and obesity. As a more complicated but also more realistic alternative, we also analyzed a case with endogenous prices of food and farm commodities. For this case we used own-price elasticities of the supply of farm commodities based on the lower- and upper-bound estimates of Chavas and Cox (1995), denoted as ε_{Lower} and ε_{Upper}, respectively. Because the farm commodities in Chavas and Cox do not exactly correspond to the farm commodities being analyzed in this study, we assumed that each of the disaggregated commodities has the same own-price elasticities as their corresponding aggregate commodity group (table 3). Lastly, we assumed that the elasticity of supply of the marketing input is large and close to being perfectly elastic. We discuss in detail the results using the lower-bound estimates of supply elasticities from Chavas and Cox (1995) compared with the results using perfectly elastic supply. These two sets of results bracket those from using the upper-bound estimates of supply elasticities from Chavas and Cox (1995), which are reported to further illustrate the effects of the values of the supply elasticities on the simulation results.

We estimated the farm-retail product shares (**SR**), farm-commodity shares (**SC**) and values for the total output of retail products and commodities ($\mathbf{D}_{WX}$ and $\mathbf{D}^{PQ}$, respectively) using the Detailed Use Table (after redefinitions) from the 2002 Benchmark Input-Output (I-O)

[6] Okrent and Alston (2011) estimated these elasticities specifically with the present application in mind. They estimated the National Bureau of Research (NBR) model (Neves 1987) with annual Personal Consumption Expenditures and Fisher-Ideal price indexes from 1960 to 2009 (U.S. Department of Commerce, Bureau of Economic Analysis 2010). They evaluated these elasticities and preferred them compared with those from other models they estimated (that were dominated statistically by the NBR model) and compared with others from the literature.

Table 2a. Marshallian Elasticities of Demand for FAH and FAFH Products

	With Respect to Price of										
Elasticity of Demand for	Cereals & Bakery	Meat	Eggs	Dairy	Fruits & Vegetables	Other Food	Nonalcoholic Beverages	FAFH	Alcoholic Beverages	Nonfood	With Respect to Total Expenditure
Cereals & bakery	−0.93	0.04	0.02	0.14	0.13	0.45	−0.04	−0.42	−0.06	0.39	0.28
	(0.13)	(0.10)	(0.03)	(0.09)	(0.10)	(0.10)	(0.07)	(0.19)	(0.13)	(0.38)	(0.26)
Meat	0.02	−0.40	0.05	0.00	0.16	−0.12	−0.09	0.23	0.20	−0.69	0.64
	(0.05)	(0.13)	(0.02)	(0.05)	(0.05)	(0.07)	(0.05)	(0.10)	(0.06)	(0.33)	(0.32)
Eggs	0.24	1.00	−0.73	0.66	−0.47	−0.54	0.27	0.25	−0.20	0.22	−0.69
	(0.29)	(0.36)	(0.14)	(0.28)	(0.30)	(0.32)	(0.22)	(0.54)	(0.37)	(1.25)	(0.95)
Dairy	0.16	0.00	0.08	−0.91	−0.09	0.26	0.20	−0.26	0.17	−0.59	0.97
	(0.11)	(0.13)	(0.04)	(0.14)	(0.11)	(0.11)	(0.08)	(0.21)	(0.14)	(0.46)	(0.34)
Fruits & vegetables	0.14	0.32	−0.05	−0.07	−0.58	−0.15	0.11	0.20	−0.03	−0.16	0.27
	(0.11)	(0.11)	(0.03)	(0.09)	(0.14)	(0.10)	(0.07)	(0.19)	(0.13)	(0.38)	(0.26)
Other food	0.33	−0.17	−0.04	0.15	−0.11	−0.62	0.05	0.12	0.00	−0.50	0.79
	(0.07)	(0.10)	(0.02)	(0.07)	(0.07)	(0.11)	(0.06)	(0.12)	(0.08)	(0.34)	(0.28)
Nonalcoholic beverages	−0.06	−0.22	0.03	0.21	0.13	0.08	−0.77	−0.08	0.18	−0.37	0.86
	(0.08)	(0.12)	(0.03)	(0.08)	(0.08)	(0.10)	(0.10)	(0.14)	(0.10)	(0.42)	(0.36)
FAFH	−0.15	0.13	0.01	−0.07	0.06	0.05	−0.02	−0.55	−0.12	−0.19	0.84
	(0.06)	(0.06)	(0.02)	(0.05)	(0.06)	(0.05)	(0.04)	(0.20)	(0.09)	(0.24)	(0.13)
Alcoholic beverages	−0.05	0.24	−0.02	0.10	−0.02	0.00	0.10	−0.22	−0.50	−0.13	0.50
	(0.09)	(0.08)	(0.03)	(0.07)	(0.08)	(0.08)	(0.05)	(0.18)	(0.16)	(0.34)	(0.19)
Nonfood	0.00	−0.03	0.00	−0.01	−0.01	−0.02	−0.01	−0.02	−0.02	−0.94	1.07
	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.01)	(0.01)	(0.03)	(0.02)

Note: Elasticities evaluated at means of sample data, taken from Okrent and Alston (2011). Standard errors are in parentheses.

Table 2b. Simulated Marshallian Elasticities of Demand that Satisfy Curvature and Monotonicity for FAH and FAFH Products

	With Respect to Price of										
Elasticity of Demand for	Cereals & Bakery	Meat	Eggs	Dairy	Fruits & Vegetables	Other Food	Nonalcoholic Beverages	FAFH	Alcoholic Beverages	Nonfood	With Respect to Total Expenditure
Cereals & bakery	−0.98	0.07	0.02	0.11	0.17	0.43	−0.05	−0.36	−0.08	0.46	0.21
	(0.13)	(0.09)	(0.03)	(0.09)	(0.09)	(0.09)	(0.06)	(0.18)	(0.12)	(0.36)	(0.25)
Meat	0.03	−0.51	0.05	0.01	0.14	−0.09	−0.10	0.21	0.18	−0.67	0.75
	(0.05)	(0.10)	(0.02)	(0.05)	(0.05)	(0.06)	(0.05)	(0.09)	(0.06)	(0.32)	(0.31)
Eggs	0.23	0.96	−0.74	0.66	−0.48	−0.53	0.28	0.22	−0.19	0.28	−0.69
	(0.29)	(0.34)	(0.14)	(0.27)	(0.29)	(0.31)	(0.22)	(0.52)	(0.35)	(1.25)	(0.93)
Dairy	0.13	0.02	0.08	−0.94	−0.07	0.24	0.19	−0.21	0.15	−0.51	0.92
	(0.11)	(0.11)	(0.03)	(0.13)	(0.10)	(0.11)	(0.07)	(0.20)	(0.13)	(0.44)	(0.32)
Fruits & vegetables	0.18	0.28	−0.05	−0.05	−0.63	−0.12	0.12	0.12	−0.04	−0.15	0.35
	(0.10)	(0.10)	(0.03)	(0.09)	(0.13)	(0.09)	(0.06)	(0.18)	(0.12)	(0.37)	(0.26)
Other food	0.31	−0.11	−0.04	0.14	−0.09	−0.65	0.05	0.16	0.01	−0.50	0.72
	(0.07)	(0.08)	(0.02)	(0.07)	(0.07)	(0.11)	(0.06)	(0.11)	(0.08)	(0.31)	(0.26)
Nonalcoholic beverages	−0.08	−0.25	0.03	0.20	0.14	0.09	−0.78	−0.04	0.15	−0.36	0.90
	(0.08)	(0.12)	(0.03)	(0.08)	(0.08)	(0.10)	(0.10)	(0.13)	(0.09)	(0.42)	(0.36)
FAFH	−0.13	0.12	0.01	−0.06	0.03	0.07	−0.01	−0.64	−0.10	−0.17	0.89
	(0.06)	(0.05)	(0.02)	(0.05)	(0.06)	(0.05)	(0.03)	(0.17)	(0.08)	(0.22)	(0.13)
Alcoholic beverages	−0.06	0.23	−0.01	0.08	−0.03	0.01	0.08	−0.18	−0.57	−0.04	0.49
	(0.08)	(0.07)	(0.02)	(0.07)	(0.08)	(0.07)	(0.05)	(0.16)	(0.14)	(0.31)	(0.19)
Nonfood	−0.00	−0.03	−0.00	−0.01	−0.01	−0.02	−0.01	−0.02	−0.01	−0.95	1.06
	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.03)	(0.02)

Note: Simulations were based on estimates of parameters and their covariances from Okrent and Alston (2011). Standard deviations are in parentheses.

Table 3. Own-Price Elasticities of Supply of U.S. Farm Commodities and a Marketing Input

	ε_{Lower}	ε_{Upper}
Oilseed crops	0.60	1.31
Sugar cane & beets	0.60	1.31
Other crops	0.60	1.31
Food grains	0.59	2.93
Vegetables & melons	0.42	1.77
Fruits & tree nuts	0.44	1.65
Cattle	0.81	1.61
Other animals	0.81	1.61
Milk	0.81	1.61
Poultry	0.81	1.61
Fish	0.40	0.40
Marketing input	1000	1000

Notes: Based on Chavas and Cox (1995).

Accounts (U.S. Department of Commerce, Bureau of Economic Analysis 2007). The Detailed Use Table shows the use of farm commodities, retail products, and services by different industries (intermediate input use) and final users (personal consumption, net imports, private fixed investment, inventories, and government). The estimated shares and retail product and commodity values for 2002 are presented in tables 4, 5, and 6.

Once the proportionate changes in quantities of retail products have been calculated for a given policy using the model as represented in (27), the changes in quantities consumed can be translated into measures of changes in calorie consumption and changes in weight (η^{WQ}). First, we used one day of 24-hour dietary recall data collected in the 2003-04 National Health and Nutrition Examination Survey (NHANES) to estimate average daily grams of the nine foods consumed, as well as the associated average daily calories, and grams of fat and added sugar for individuals 18 years and older (table 7). Second, we converted the changes in calorie consumption resulting from a policy to changes in body weight for the average individual adult. One frequently used relationship in textbooks (e.g. Whitney, Cataldo, and Rolfes 1994) and academic articles that address the potential impacts of fiscal policies on weight (e.g. Chouinard et al. 2007; Smith, Lin and Lee 2010) is that a pound of fat tissue contains about 3,500 calories. We used this multiplier to convert changes in annual calorie consumption into changes in body weight.[7]

Lastly, we quantify changes in public health care expenditures associated with policy-induced changes in food consumption using the multiplier from Parks, Alston, and Okrent (2011), who estimated that a one-pound increase in average adult body weight would increase public health expenditures by \$2.66 for a nationally representative sample. To obtain this estimate, Parks, Alston, and Okrent (2011) estimated a two-part model (Cameron and Trivedi 2005, p. 545) of public medical expenditures (the sum of medical payments by Medicaid, Medicare, other Federal, other public, Veterans Affairs, TRICARE, and other state and local government) as a function of BMI, the square of BMI, age, the square of age, race, and sex, using data from the 2008 wave of the Medical Expenditure Panel Survey (MEPS). The authors used the results from the two-part model to calculate the unconditional marginal effects of the explanatory variables on public medical expenditures and to predict public medical expenditures as a function of the explanatory variables for the U.S. adult population using both (a) the actual NHANES 2007-2008 data on the distribution of the population by weight and height, and (b) a counterfactual distribution in which each person had gained one pound. Thus, they estimated the change in public health care expenditures for a one pound per person increase in body weight for the entire adult population as being \$2.66 per pound per person, which is equivalent to $e = \$604.8$ million in total per pound per capita increase in average adult body weight. We use this multiplier as a measure of the impact of policy-induced changes

[7] The relationship between caloric consumption and obesity is clearly much more complex than this use of a simple, fixed multiplier would suggest, and has significant nonlinear and dynamic aspects. Nevertheless, such treatments are common in models of obesity and policy. In the analysis presented in this paper, we are simulating a change in policy of the type that would typically be implemented on an enduring basis. The resulting changes in consumption would therefore be ongoing, and the consequent annual changes in bodyweight would be cumulative. We abstract from the detail of these difficult dynamics in our analysis, which is explicitly comparatively static in nature. However, we deal with these dynamics effectively through our use of multiplier that is consistent with the steady-state impacts of policy changes. A small number of studies have estimated the change in steady-state weight for a permanent change in caloric consumption, which is a relevant concept for our context. Hall et al. (2009) developed a formula (equation 14, p. 5) which implies that an increase in consumption of 220 kcal per day would be consistent with an increase in body weight of 10 kg (which translates approximately to a 10 kcal per day per pound increase of steady state-body weight). Hall and Jordan (2008) reported tables of multipliers such that, for a 115 kg man or a 90 kg woman, a permanent decrease in consumption of 100 kcal per day would result in a steady-state weight loss of 6.4 kg, which translates to 7.1 kcal per day per pound. The figure of 3,500 kcal per pound is equivalent to 9.6 kcal per day per pound, which falls between the estimates from Hall et al. (2009) and Hall and Jordan (2008). See also Hall et al. (2011).

Table 4. Farm-Retail Product Shares

	Share of Total Cost for Retail Products								
Attributable to	Cereals & Bakery	Meat	Eggs	Dairy	Fruits & Vegetables	Other Food	Nonalcoholic Beverages	FAFH	Alcoholic Beverages
Farm Commodity									
Oil-bearing crops	0.0000	0.0000	0.0000	0.0000	0.0000	0.0619	0.0000	0.0027	0.0000
Grains	0.0593	0.0000	0.0000	0.0000	0.0027	0.0345	0.0000	0.0038	0.0164
Vegetables & melons	0.0000	0.0000	0.0000	0.0000	0.2722	0.0167	0.0000	0.0020	0.0000
Fruits & tree nuts	0.0027	0.0000	0.0000	0.0012	0.2062	0.0184	0.0294	0.0018	0.0213
Sugar cane & beets	0.0000	0.0000	0.0000	0.0000	0.0000	0.0131	0.0000	0.0006	0.0000
Other crops	0.0009	0.0000	0.0000	0.0000	0.0000	0.0210	0.0038	0.0010	0.0024
Cattle production	0.0000	0.1907	0.0000	0.0000	0.0000	0.0000	0.0000	0.0094	0.0000
Other livestock production	0.0000	0.0726	0.0000	0.0000	0.0000	0.0030	0.0000	0.0046	0.0000
Dairy farming	0.0000	0.0000	0.0000	0.2739	0.0000	0.0009	0.0000	0.0096	0.0000
Poultry & egg production	0.0063	0.0923	0.6851	0.0022	0.0006	0.0039	0.0000	0.0051	0.0000
Fish production	0.0000	0.0638	0.0000	0.0000	0.0039	0.0003	0.0000	0.0072	0.0000
Marketing inputs	0.9309	0.5806	0.3149	0.7227	0.5144	0.8264	0.9668	0.9523	0.9599

Note: Authors' calculations based on 2002 Benchmark I-O Tables (U.S. Department of Commerce, Bureau of Economic Analysis 2007).

Table 5. Farm-Commodity Shares

	Attributable to Retail Product								
Share of Total Cost of	Cereals & Bakery	Meat	Eggs	Dairy	Fruits & Vegetables	Other Food	Nonalcoholic Beverages	FAFH	Alcoholic Beverages
Farm Commodity									
Oil-bearing crops	0.0000	0.0000	0.0000	0.0000	0.0000	0.8525	0.0000	0.1475	0.0000
Grains	0.3812	0.0000	0.0000	0.0000	0.0134	0.3811	0.0000	0.1670	0.0573
Vegetables & melons	0.0000	0.0000	0.0000	0.0000	0.8337	0.1133	0.0000	0.0530	0.0000
Fruits & tree nuts	0.0113	0.0000	0.0000	0.0041	0.6812	0.1347	0.0665	0.0528	0.0494
Sugar cane & beets	0.0000	0.0000	0.0000	0.0000	0.0000	0.8525	0.0000	0.1475	0.0000
Other crops	0.0186	0.0000	0.0000	0.0000	0.0000	0.7665	0.0428	0.1440	0.0281
Cattle production	0.0000	0.8374	0.0000	0.0000	0.0000	0.0000	0.0000	0.1626	0.0000
Other livestock production	0.0000	0.7769	0.0000	0.0000	0.0000	0.0313	0.0000	0.1918	0.0000
Dairy farming	0.0000	0.0000	0.0000	0.7682	0.0000	0.0054	0.0000	0.2264	0.0000
Poultry & egg production	0.0254	0.6465	0.1517	0.0073	0.0018	0.0270	0.0000	0.1403	0.0000
Fish production	0.0000	0.6777	0.0000	0.0000	0.0187	0.0027	0.0000	0.3010	0.0000
Marketing inputs	0.0781	0.0849	0.0015	0.0493	0.0335	0.1191	0.0430	0.5469	0.0439

Note: Based on 2002 Benchmark I-O Tables (U.S. Department of Commerce, Bureau of Economic Analysis 2007).

Table 6. Total Annual Value of Food Products and Farm Commodities and Marketing Inputs

	Millions of Dollars
FAH	
Cereals and bakery	55,069
Meat	103,490
Eggs	3,921
Dairy products	46,762
Fruits & vegetables	48,552
Other foods	100,308
Nonalcoholic beverages	28,672
FAFH	372,264
Alcoholic beverages	36,025
Farm commodities	
Oil-bearing crops	8,874
Grains	11,039
Vegetables & melons	17,740
Fruits & tree nuts	16,690
Sugar cane & beets	1,877
Other crops	3,321
Cattle production	28,246
Other livestock production	11,541
Dairy farming	20,632
Poultry & egg production	17,426
Fish production	11,361
Marketing inputs	646,315

Notes: Based on 2002 Benchmark I-O Tables (U.S. Department of Commerce, Bureau of Economic Analysis 2007).

in adult body weight on public health care expenditures.[8]

Table 8 summarizes all the parameters, data sources, and assumptions used to simulate tax and subsidy policies using the model.

Simulations

We simulated the price, quantity, calorie, body weight, and social welfare effects for various policies that have been suggested by policymakers and others as means of reducing the costs of obesity in the United States. The first set of policy simulations addresses the notion that subsidies to farmers are an important key driver of obesity patterns in the United States (e.g. Pollan 2003, 2007; Tillotson 2004; Muller, Schoonover, and Wallinga 2007). Agricultural economists have argued that farm subsidies have had minimal impacts on obesity (e.g. Alston, Sumner, and Vosti 2006; Alston, Sumner, and Vosti 2008; Beghin and Jensen 2008), but none of the previous studies quantified the impacts. The second set of policy simulations quantifies the effects of subsidizing fruit and vegetable commodities and fruit and vegetable retail products; both policies have been suggested by nutritionists (Tohill 2005; Guthrie 2004) and mentioned in the Farm Bill debate (Guenther 2007; Bittman 2011) as ways of addressing obesity. The third and final set of policies are taxes on the nutrient content of foods—that is, taxes on food products based on their content of calories, sugar, or fat. If the goal of a policy is to reduce the weight and hence BMI status of a population, then a calorie tax would intuitively be the most efficient tax, but proponents typically favor taxes on particular energy-dense foods (such as sodas) or sources of calories (such as sugar or fat). Several papers have examined the potential caloric and social welfare effects of nutrient or energy taxes, or both, but have all assumed perfectly elastic supply and have not considered the effects of such policies on public health care expenditures (Chouinard et al. 2007; Miao, Beghin and Jensen 2010; Smed, Jensen and Denver 2007; Salois and Tiffin 2011).

Removal of Farm Subsidies

We computed the effects of eliminating farm subsidies using estimates of their price impacts from several sources and treating commodity prices as exogenous. Sumner (2005) estimated that eliminating subsidies for corn, wheat, and rice would increase the world prices of these crops by 9–10%, 6–8%, and 4–6%, respectively, based on market prices and policies in the early 21st century. Using the value of U.S. production of each crop relative to their sum as weights, we calculated the value-share-weighted effect of the elimination of grain subsidies on the composite food grain price as being an 8.4% increase (table 9). Eliminating the corn subsidy would also affect the price of feed grains, and hence, the cost of production and prices of livestock commodities. The effect that removing corn subsidies would have on the price of a livestock commodity is computed as the percentage change in the world market price of corn from the elimination of the subsidy, multiplied by the cost share of corn in the production of that commodity.

Applying these implied price changes in the simulation model, eliminating farm subsidies

[8] Parks, Alston, and Okrent (2011) also estimated a Tobit model in which the corresponding multiplier was $e = \$655.3$ million.

Table 7. Average Daily Quantities of Food, Sugar and Fat and Energy Intake by Food Group for Individuals Aged 18 and Older, 2003–2004 and 2002 Per Capita Budget Shares

	Energy	Quantity	Sugar	Fat	Budget Share	Body Weight to Food Multiplier[a]
	kcal	*grams*	*grams*	*grams*	*percentage*	*pounds/kilograms*
Total	2,274.79	2,609.23	86.23	129.38		
FAH						
Cereals & bakery	351.94	133.04	9.38	16.37	9.46	0.76
Meat	162.20	67.59	9.85	0.22	11.02	0.69
Eggs	34.26	20.72	2.47	0.36	0.57	0.47
Dairy	166.13	186.49	8.38	13.80	4.35	0.25
Fruits & vegetables	124.36	195.58	2.41	12.88	6.97	0.18
Other food	362.30	183.11	18.25	13.43	13.14	0.57
Nonalcoholic beverages	178.48	925.31	1.10	36.29	6.44	0.06
FAFH	821.38	710.94	35.19	36.31	34.48	0.33
Alcohol	122.05	272.12	0.01	1.38	13.58	0.13

Note: Calculations for the consumption of foods and associated nutrient and energy content are based on one day of dietary recall data for respondents aged 18 or older from the 2003–2004 NHANES (Centers for Disease Control and Prevention, National Center for Health Statistics 2007). The budget shares are based on 2002 personal consumption expenditures (U.S. Department of Commerce, Bureau of Economic Analysis, National Income and Product Accounts 2010).
[a]The pounds of body weight to kilograms of food consumption multiplier (i.e. $\partial B/\partial Q^n$) is calculated as energy per gram of food consumed (i.e. kcal/kilogram) times 1 pound of body fat tissue per 3,500 calories (lbs/kcal); $\partial B/\partial Q^n$ is used to calculate the elasticity of body weight with respect to consumption of food (i.e. $\eta^{B,Q} = \partial B/\partial Q^n \times Q^n/B$) and the change in pounds of body weight from a policy (i.e. $dB = \partial B/\partial Q^n \times EQ^n \times Q^n$).

on grain commodities would result in a decrease in consumption of 567 calories per adult per year, which corresponds to a decrease in body weight of 0.16 kilograms per year for an average adult in the United States (table 10, panel a). The probability that the removal of farm subsidies on grain commodities would result in a decrease in calorie consumption is 94% based on the empirical posterior distribution estimated using Monte Carlo integration. Removing the U.S. grain subsidy would increase social welfare, but the actual magnitude of the net gain cannot be determined using the social welfare measure presented in this paper because this measure does not reflect the government revenue effects of changes in border measures or other details of the actual subsidies that are represented in our analysis as fully coupled equivalent rates.

Some agricultural policies entail benefits or costs to consumers in addition to those implied by changes in world market prices, including trade barriers for sugar, dairy, and some fruit and vegetable commodities. To capture the effects of these policies on commodity prices paid by buyers, we used the commodity-specific consumer support estimates (CSEs) calculated by the Organization for Economic Co-operation and Development (2010) for three periods: 1989–2009, 2000–2009, and 2006 (table 9).

The removal of border measures would result in lower prices and increases in the consumption of some commodities (table 10, panel a). We represented this policy in the model as the introduction of an equivalent set of subsidies in conjunction with the removal of the other farm subsidies already discussed. The net effect would be to increase calorie consumption. Not surprisingly, calories from the consumption of dairy and fruit and vegetable food products would increase (by 1,744 kcal and 836 kcal, respectively) if subsidies were introduced that would have effects equivalent to eliminating the 2006 CSEs. Compared to eliminating only grain subsidies, eliminating all farm subsidies would result in a larger reduction in the consumption of calories of cereals and bakery products (−1,458 kcal versus −448 kcal). This result is driven by greater substitution out of cereals and bakery products into fruits and vegetables and dairy because the increase in the price of grain commodities is now accompanied by a reduction in the price of milk, fruit, and vegetable commodities.

Eliminating all subsidies, including trade barriers, would lead to an increase in annual per capita consumption in the range of 165 to 1,435 calories (equivalent to an increase in body weight of 0.03% to 0.23%), depending on the size of the policy-induced price wedges to be removed, as represented by the CSEs. The probability of increased calorie

Table 8. Description of Parameters and Assumptions Used in the Simulations

		Description	Source	Table
Parameters for equilibrium displacement model				
Elasticities of demand for retail products	$\boldsymbol{\eta}^N$	9 × 9 matrix (homogeneity, adding-up imposed)	Authors' simulated values, based on Okrent and Alston (2011).	2
Elasticities of supply of farm commodities	$\boldsymbol{\varepsilon}_L$	12 × 12 diagonal matrix (no cross-price effects); ∞	Authors' calculations based on upper- and lower-bound estimates of Chavas and Cox (1995).	3
Farm-retail product shares	**SR**	12 × 9 matrix	Authors' calculations based on 2002 Benchmark Input-Output Accounts.	4
Farm-commodity shares	**SC**	12 × 9 matrix	Authors' calculations based on 2002 Benchmark Input-Output Accounts.	5
Hicksian elasticities of demand for commodities	$\boldsymbol{\eta}_L^*$	12 × 12 zero matrix	Fixed proportions assumption	–
Commodity subsidies	$\mathbf{s}_L$	12 × 1 vector	Authors' calculations based on Sumner (2005) and Rickard, Okrent and Alston (2011).	8
Retail product taxes	$\mathbf{t}^N$	9 × 1 vector	Authors' calculations based on 2003-04 NHANES assuming \$5 tax per gram of fat, or near equivalent.	10, A-1
Additional parameters for social welfare model				
Budget shares	**w**	9 × 1 vector	Authors' calculations based on 2002 Personal Consumption Expenditures in the National Income and Product Accounts	7
Value of total output for retail products	$\mathbf{D}_{WX}$ ($\mathbf{D}_W\mathbf{X}$)	12 × 12 diagonal matrix (12 × 1 vector)	Authors' calculations based on 2002 Benchmark Input-Output Accounts	6
Value of total output for commodities	$\mathbf{D}_{PQ}$ ($\mathbf{D}_P\mathbf{Q}$)	9 × 9 diagonal matrix (9 × 1 vector)	Authors' calculations based on 2002 Benchmark Input-Output Accounts	6
Parameters for health care expenditures related to obesity				
Marginal increase in public health expenditures for increase in weight	e	scalar	Parks, Alston and Okrent (2011)	e = \$604.8 million per pound per adult
Elasticity of body weight with respect to food consumption	$\boldsymbol{\eta}^{BQ}$	9 × 1 vector	Authors' calculations based on 2003-04 NHANES and assuming 3,500 kcal per year contributes one pound of body fat	7

consumption is 60% or 80%, depending on which CSE is used. Even though individuals would consume less calories from cereals and bakery products and FAFH, they would consume more calories from dairy products and fruits and vegetables. These results indicate that U.S. farm policy, for the most part, has not made food commodities significantly cheaper and has not had a significant effect on caloric consumption.

Table 9. Commodity Policies Simulated

	Elimination of Grain Subsidies	Elimination of Grain Subsidies and Trade Barriers Based on CSEs in 2006	Elimination of Grain Subsidies and Trade Barriers Based on CSEs in 2000–2009	Elimination of Grain Subsidies and Trade Barriers Based on CSEs in 1989–1999	16.24% Subsidy on Fruit & Vegetable Commodities
			Percentage Tax Equivalents		
Oilseed	0.00	0.00	0.00	0.00	0.00
Food grains	−8.40	−8.40	−8.40	−8.40	0.00
Vegetables & melons	0.00	4.00	4.00	4.00	16.24
Fruits & tree nuts	0.00	6.00	6.00	6.00	16.24
Sugar cane & beets	0.00	31.00	54.20	55.69	0.00
Other crops	0.00	0.00	0.00	0.00	0.00
Beef cattle	−2.85	−2.85	−2.85	−2.85	0.00
Hogs & other meat animals	−2.85	−2.85	−2.85	−2.85	0.00
Milk[a]	−2.85	9.55	24.95	31.78	0.00
Poultry & eggs	−4.75	−4.75	−4.75	−4.75	0.00
Fish & aquaculture	0.00	0.00	0.00	0.00	0.00

Note: Authors' calculations based on Sumner (2005), and Rickard, Okrent, and Alston (2011). Entries are ad valorem tax equivalents in the context of the model. A commodity policy with $s_l < 0$ denotes a tax on commodity l and a commodity policy with $s_l > 0$ denotes a subsidy on commodity l.
[a] Eliminating corn subsidies would implicitly increase the price of milk by 2.85%. If grain subsidies and trade barriers as captured by the CSE for milk in 2006 were removed, then the price of milk would increase by 9.55% (= −2.85% + 12.4%).

Subsidies Applied to Fruits and Vegetables

We estimated the likely effects from two types of subsidies applied to fruits and vegetables: (a) subsidies applied to fruit and vegetable retail products at a rate of 10%, and (b) subsidies applied to fruit and vegetable farm commodities at a rate of approximately 16.24 % (table 11). The subsidy rate of 16.24% on fruit and vegetable commodities was chosen so that the cost of both policies would be roughly equal to $5,846 million per year given our baseline assumptions and exogenous prices.

In the case of exogenous commodity prices, a 10% subsidy on fruit and vegetable retail products would cause the consumption of fruits and vegetables to increase (table 10, panel a). However, because fruits and vegetables are substitutes for cereals and bakery products, meat, nonalcoholic beverages and FAFH, consumption of these foods, and hence, calories taken from them would decrease (by 2,172 kcal per year, 829 kcal per year, 907 kcal per year, and 913 kcal per year, respectively). The net effect of a policy of subsidizing fruit and vegetable retail products at 10% would be to increase calorie consumption by 343 calories per year for an average adult in the United States. However, the total caloric effect of the policy is measured somewhat imprecisely, with a fairly large standard deviation around the posterior mean (i.e. 2,076).

A slightly different story unfolds when we allow for an upward-sloping supply of farm commodities (table 10, panel b). Specifically, consider the results using the lower-bound estimates of supply elasticities. In this case the subsidy on fruit and vegetable retail products would increase overall calorie consumption but the effect is much smaller (16 kcal per year compared with 343 kcal per year). When the supply of farm commodities is less than perfectly elastic, the effect of the fruit and vegetable product subsidy on food prices, and thus on consumption, is smaller across all food products, but especially smaller for food products that have relatively large farm-retail product shares. The food products with the biggest farm-retail product shares include eggs, dairy, and fruits and vegetables. Hence, when we allow for an upward-sloping commodity supply, the effect of the subsidy policy on consumption of these food products is dampened to a much greater degree compared with FAFH and cereals and bakery products, which have relatively small farm-retail product shares. The result is a larger decrease in calories consumed per year for foods that are substitutes for fruits and vegetables, relative to the increase in calories consumed per year for fruits and vegetables and its complements. Ultimately, average body weight would increase by less than 0.01 pounds per adult per year under the assumption of upward-sloping supply. It should

Table 10. Change in Annual Calorie Consumption and Body Weight per Adult

a. Assuming Commodity Prices are Exogenous ($\varepsilon = \infty$)

	Change in calorie consumption											
	Cereal & Bakery	Meat	Eggs	Dairy	F & V	Other Food	Nonalcohol Drinks	FAFH	Alcohol Drinks	Total	Change in Body Weight	Probabilities that Change in Body Weight < 0
						Calories					*Pounds*	
Removal of grain subsidies only	−448	−242	−231	702	109	−541	−214	282	16	−567	−0.16	0.94
	(189)	(74)	(66)	(124)	(73)	(164)	(103)	(255)	(55)	(370)	(0.11)	
Removal of all subsidies												
2006 CSE	−1,458	−430	−212	1,744	836	−155	−615	493	7	210	0.06	0.39
	(468)	(131)	(141)	(289)	(198)	(353)	(205)	(618)	(132)	(834)	(0.24)	
2000–2009 CSE	−2,175	−457	−544	4,132	941	−721	−1,171	1,422	−139	1,288	0.37	0.22
	(868)	(231)	(257)	(596)	(325)	(665)	(382)	(1,173)	(245)	(1,641)	(0.47)	
1989–2009 CSE	−2,431	−474	−699	5,207	981	−1,071	−1,411	1,848	−204	1,747	0.50	0.19
	(1,065)	(282)	(315)	(743)	(393)	(822)	(470)	(1,450)	(301)	(2,036)	(0.58)	
F&V product subsidy	−2,172	−829	599	406	2,870	1,166	−907	−913	123	343	0.10	0.42
	(1,177)	(299)	(366)	(633)	(589)	(877)	(492)	(1,619)	(335)	(2,076)	(0.59)	
F&V commodity subsidy	−1,858	−631	490	161	2,234	1,327	−527	−571	168	795	0.23	0.30
	(901)	(231)	(279)	(489)	(452)	(669)	(376)	(1,239)	(256)	(1,595)	(0.46)	
Fat tax	−2,259	−192	−1,025	−4,023	−353	−3,349	808	−10,688	181	−20,901	−5.97	1.00
	(1,877)	(616)	(631)	(1,201)	(678)	(1,572)	(995)	(3,030)	(507)	(4,652)	(1.33)	
Calorie tax	−6,907	48	−717	1,500	−116	−1,534	−2,392	−8,903	−546	−19,567	−5.59	1.00
	(1,322)	(413)	(410)	(755)	(453)	(1,009)	(699)	(2,029)	(380)	(3,203)	(0.92)	
Sugar tax	−4,756	−156	894	−3,114	−491	2,373	−6,927	−8,742	451	−20,467	−5.85	1.00
	(2,019)	(659)	(633)	(1,218)	(668)	(1,743)	(1,360)	(2,395)	(482)	(4,753)	(1.36)	
Uniform tax	−4,338	−233	258	−1,266	−445	−1,461	−1,765	−10,505	−1,007	−20,762	−5.93	1.00
	(1,659)	(559)	(541)	(982)	(594)	(1,301)	(925)	(2,543)	(501)	(4,103)	(1.17)	

Note: These estimates are based on the special case of exogenous commodity prices using the general price transmission model. The estimates are the means of the posterior distributions from the Monte Carlo simulations. The numbers in parentheses represent the standard deviations of the means of the posterior distribution. The probability that a policy will induce a negative change in body weight is the area under the posterior distribution of the change in body weight to the left of zero. F&V represents fruit & vegetables.

Table 10. Change in Annual Calorie Consumption and Body Weight per Adult

b. Assuming Upward-Sloping Supply of Commodities ($\varepsilon < \infty$)

	Change in calorie consumption											
	Cereal & Bakery	Meat	Eggs	Dairy	F & V	Other Food	Nonalcohol Drinks	FAFH	Alcohol Drinks	Total	Change in Body Weight	Probabilities that Change in Body Weight < 0
	Calories										*Pounds*	
ε_{Lower}												
F&V product subsidy	−1,279	−460	356	273	1,798	619	−589	−730	29	16	0.00	0.49
	(713)	(164)	(224)	(333)	(258)	(542)	(317)	(1,056)	(219)	(1,335)	(0.38)	
F&V commodity subsidy	−1,140	−345	289	92	1,382	838	−284	−410	91	513	0.15	0.29
	(533)	(123)	(167)	(253)	(193)	(400)	(237)	(788)	(162)	(998)	(0.29)	
Fat tax	−2,678	−115	−981	−3,180	−139	−2,966	597	−10,296	116	−19,642	−5.61	1.00
	(1,676)	(473)	(541)	(882)	(422)	(1,334)	(884)	(2,854)	(475)	(4,124)	(1.18)	
Calorie tax	−5,951	111	−205	−1,578	−111	−212	−1,657	−9,513	−318	−19,434	−5.55	1.00
	(1,387)	(380)	(410)	(692)	(321)	(1,034)	(767)	(2,062)	(376)	(3,452)	(0.99)	
Sugar tax	−4,741	−131	748	−2,280	−276	2,131	−6,852	−8,269	407	−19,264	−5.50	1.00
	(1,823)	(519)	(541)	(892)	(410)	(1,501)	(1,280)	(2,205)	(448)	(4,264)	(1.22)	
Uniform tax	−4,443	−157	243	−915	−214	−1,130	−1,794	−10,165	−992	−19,565	−5.59	1.00
	(1,512)	(436)	(469)	(739)	(370)	(1,119)	(842)	(2,440)	(480)	(3,741)	(1.07)	
ε_{Upper}												
F&V product subsidy	−1,919	−674	514	347	2,550	1,039	−773	−906	83	261	0.07	0.43
	(1,041)	(241)	(317)	(508)	(484)	(763)	(440)	(1,463)	(303)	(1,865)	(0.53)	
F&V commodity subsidy	−1,642	−510	417	134	1,970	1,192	−424	−552	135	720	0.21	0.29
	(789)	(185)	(239)	(390)	(368)	(576)	(334)	(1,108)	(228)	(1,418)	(0.41)	
Fat tax	−2,506	−109	−1,031	−3,546	−302	−3,200	719	−10,518	125	−20,368	−5.82	1.00
	(1,782)	(522)	(583)	(1,017)	(592)	(1,447)	(934)	(2,931)	(489)	(4,387)	(1.25)	
Calorie tax	−5,989	130	−222	−1,789	−227	−298	−1,601	−9,708	−333	−20,036	−5.72	1.00
	(1,464)	(416)	(440)	(793)	(451)	(1,114)	(796)	(2,110)	(385)	(3,636)	(1.04)	
Sugar tax	−4,709	−101	781	−2,617	−448	2,186	−6,814	−8,429	403	−19,750	−5.64	1.00
	(1,915)	(562)	(577)	(1,022)	(578)	(1,602)	(1,303)	(2,273)	(461)	(4,480)	(1.28)	
Uniform tax	−4,394	−144	220	−1,054	−400	−1,324	−1,746	−10,310	−1,020	−20,172	−5.76	1.00
	(1,594)	(476)	(500)	(843)	(523)	(1,203)	(876)	(2,482)	(491)	(3,918)	(1.12)	

Note: See Table 10a.

Table 11. Food Policies Simulated: Ad Valorem Tax Equivalents

	10 % Subsidy on Fruit and Vegetables	$0.005 Tax Per Gram Fat	$0.000165 Tax Per Calorie[a]	$0.002688 Tax Per Gram Sugar[a]	5.03% Tax Uniform Tax on Food Products[a]
			percentage taxes		
Cereals & bakery	0.00	5.50	6.81	5.16	5.03
Meat	0.00	4.95	2.69	0.06	5.03
Eggs	0.00	24.06	11.01	1.86	5.03
Dairy	0.00	10.69	7.00	9.47	5.03
Fruits & vegetables	−10.00	1.92	3.27	5.51	5.03
Other food	0.00	7.70	5.05	3.05	5.03
Nonalcoholic beverages	0.00	0.94	5.07	16.81	5.03
FAFH	0.00	5.66	4.25	3.07	5.03
Alcoholic beverages	0.00	0.0035	1.64	0.30	5.03

Note: Entries are ad valorem tax equivalents in the context of the model. A retail product policy with $t^n > 0$ denotes a tax on food product $n$and a retail food product policy with $t^n < 0$ denotes a subsidy on food product n.

[a]These tax rates reflect the assumption of exogenous commodity prices and are constructed to achieve approximately the same calorie reduction as the $.005 tax per gram fat. The tax rates on sugar and calories for the case of endogenous commodity prices differ slightly (i.e. $t = \$0.002637$ tax per gram sugar, $t = \$0.0001632$ tax per calorie, and $t = 4.973\%$ uniform tax). Hence, the ad valorem taxes for each food product for the case of endogenous commodity prices are also slightly different.

be noted that under both assumptions about commodity supply, the 10% subsidy on fruit and vegetable products has very little impact on calorie consumption.

Suppose the government were to spend the same amount of money but chose to subsidize fruit and vegetable farm commodities rather than use a 10% subsidy on fruit and vegetable food products. This would translate into a 16.24% subsidy on fruit and vegetable commodities, depending on the assumptions made about the supply of commodities. Subsidies on fruit and vegetable commodities would cause consumption of calories to increase to a much greater extent than subsidies on fruit and vegetable products would. The difference arises largely because fruit and vegetable commodities are used as inputs in the production of FAFH, and consequently a subsidy on fruit and vegetable commodities reduces the cost of FAFH production, as well as fruit and vegetable retail products. Consumers would still substitute away from FAFH and towards now relatively cheaper fruits and vegetables, but this effect is dampened by the implicit subsidy to FAFH from the fruit and vegetable commodity subsidies. Hence, the reduction in calories consumed from FAFH is smaller under the fruit and vegetable farm commodity subsidy compared with the fruit and vegetable retail product subsidy, and the net effect is an increase in calories consumed. Assuming that the supply of commodities is perfectly elastic, calories consumed from FAFH would decrease by 571 kcal per adult per year in response to the subsidy on fruit and vegetable commodities, which is substantially less than the decrease in calories consumed from FAFH caused by the subsidy on fruit and vegetable products (913 kcal per adult per year). The same rationale holds for both scenarios of upward-sloping supply of commodities. However, the mean changes in total calorie consumption from the fruit and vegetable commodity subsidies implied by the empirical posterior distribution have large standard deviations, and the probability of the mean effect being positive is only 50% or 70%, depending on the assumptions about the elasticity of commodity supply.

If the objective is to reduce the consumption of calories and body weight, these results imply that a tax, not a subsidy, should be applied to fruit and vegetable farm commodities. Given that the model is approximately linear over the small changes being analyzed, the effects of a tax can be seen by multiplying all the results for a subsidy by minus one in table 10.[9] For comparison with other policies aiming to reduce food consumption and obesity, in table 12 we report the welfare impacts of taxes (rather than subsidies) on fruit and vegetable commodities and products, along with other food tax policies.

Consider a tax on fruit and vegetable retail products. In the case of perfectly elastic supply, the net change in social welfare would be

[9] The equilibrium displacement model and measure of public health care costs associated with obesity are linear but the measure of social welfare is nonlinear in the tax rate chosen.

Table 12. Net Social Costs of Selected Policies

a. Assuming Exogenous Prices of Commodities ($\varepsilon = \infty$)

	Annual Change in Social Welfare (ΔSW) Excluding Changes in Public Heath-Care Costs	Annual Change in Public Health Care Costs	ΔSW Including Change in Public Health Care Costs	Probability that ΔSW Including Public Health Care Costs > 0	Change in Pounds per Year of Body Weight for all U.S. Adults[b]	Annual Cost per Pound Decrease in Body Weight[a]: Excluding Changes in Public Health Care Costs	Annual Cost per Pound Decrease in Body Weight[a]: Including Changes in Public Health Care Costs
		Millions of Dollars			*Millions of Pounds*	*Dollars per Pound*	
F & V product tax	−181	−59	−122	0.37	−22	8.22	5.54
	(37)	(359)	(365)				
F & V commodity tax	−117	−137	20	0.55	−52	2.25	−0.38
	(22)	(276)	(278)				
Fat tax	−1,937	−3,612	1,675	0.99	−1,358	1.42	−1.23
	(235)	(804)	(653)				
Calorie tax	−1,102	−3,381	2,280	1.00	−1,271	0.86	−1.79
	(109)	(554)	(483)				
Sugar tax	−1,305	−3,537	2,232	1.00	−1,330	0.98	−1.67
	(170)	(821)	(694)				
Uniform tax	−1,587	−3,588	2,000	1.00	−1,349	1.17	−1.48
	(183)	(709)	(600)				

Note: These estimates were calculated using 1,110 draws from the posterior distribution that satisfied monotonicity and curvature locally. The estimates refer to the mean of the posterior distribution for each variable, and the numbers in parentheses represent the standard deviation.

[a] Evaluated at posterior means of data.

[b] The U.S. population aged 18 and older in 2008 was 227,364,210 (Parks, Alston, and Okrent 2011).

Table 12. Net Social Costs of Selected Policies

b. Assuming Upward-Sloping Supply of Commodities ($\varepsilon < \infty$)

	Annual Change in Social Welfare (ΔSW) Excluding Changes in Public Heath-Care Costs	Annual Change in Public Health Care Costs	ΔSW Including Change in Public Health Care Costs	Probability that ΔSW Including Public Health Care Costs > 0	Change in Pounds per Year of Body Weight for all U.S. Adults[b]	Annual Cost per Pound Decrease in Body Weight[a]: Excluding Changes in Public Health Care Costs	Annual Cost per Pound Decrease in Body Weight[a]: Including Changes in Public Health Care Costs
		Millions of dollars			*Millions of pounds*	*Dollars per Pound*	
ε_{Lower}							
F & V product tax	−112	−3	−109	0.29	−1	112.21	109.15
	(16)	(231)	(228)				
F &V commodity taxes	−71	−89	18	0.18	−33	2.51	−0.54
	(9)	(172)	(172)				
Fat tax	−1,717	−3,394	1,677	1.00	−1,276	1.34	−1.31
	(185)	(713)	(600)				
Calorie tax	−1,131	−3,358	2,228	1.00	−1,262	0.90	−1.77
	(112)	(596)	(526)				
Sugar tax	−1,159	−3,329	2,169	1.00	−1,251	0.93	−1.73
	(134)	(737)	(641)				
Uniform tax	−1,422	−3,381	1,959	1.00	−1,271	1.12	−1.54
	(147)	(646)	(564)				
ε_{Upper}							
F & V product tax	−161	−45	−116	0.25	−17	9.47	6.82
	(31)	(322)	(319)		(121)		
F & V commodity taxes	−103	−124	21	0.18	−47	2.19	−0.44
	(18)	(245)	(244)		(92)		
Fat tax	−1,826	−3,520	1,694	1.00	−1,323	1.38	−1.28
	(206)	(758)	(628)		(285)		
Calorie tax	−1,185	−3,462	2,277	1.00	−1,302	0.91	−1.74
	(123)	(628)	(547)		(236)		
Sugar tax	−1,210	−3,413	2,203	1.00	−1,283	0.94	−1.71
	(148)	(774)	(665)		(291)		
Uniform tax	−1,491	−3,486	1,995	1.00	−1,310	1.13	−1.53
	(161)	(677)	(583)		(255)		

a loss of $181 million per year, which is statistically significantly different from zero (table 12, panel a). This measure excludes the savings to the government from decreases in body weight. The decrease of 0.10 pounds in body weight for the average adult would reduce body weight for the entire U.S. population by 22 million pounds and save $59 million in public health care expenditures, reducing the deadweight loss to $122 million per year. The fruit and vegetable farm commodity tax would be less distortionary than the fruit and vegetable product tax (i.e. $117 million net annual cost versus $181 million) and would have a greater impact on annual public health care costs (i.e. $137 million net annual cost versus $59 million), sufficiently so that the farm commodity tax would yield a net social benefit of $20 million per year. The results are very similar in the case of upward-sloping supply, but the impacts are generally dampened (table 12, panel b).

Food Taxes

We derived ad valorem taxes for foods that would correspond to per unit taxes on their nutrient content in fat, calories, and sugar (table 11) (see Technical Appendix for more details). We arbitrarily chose a tax of half a cent per gram of fat (i.e. $5 per kilogram).[10] Subsequently, we chose the sugar tax ($0.002637 per gram) and the calorie tax ($0.0001632 per calorie) such that the resulting annual reduction in calories consumed per adult would be approximately the same under each tax policy. We also analyzed the policy of a uniform tax on all foods (roughly 5%) that would achieve approximately the same reduction in calories per day.

Fat Tax. A fat tax would cause total annual consumption of calories to decrease by 19,642 kcal per adult, with an upward-sloping supply of commodities and 20,901 kcal per adult with exogenous commodity prices. More than half of the reduction in calories consumed would come from decreased consumption of FAFH, which is a gross substitute for meat, fruits, and vegetables. In the simulation these foods are taxed at lower rates than FAFH (5.66% tax on FAFH compared to a 1.92% tax on fruits and vegetables and a 4.95% tax on meat). In addition, FAFH is a gross complement for cereals and bakery products and dairy, two of the most heavily taxed foods. Hence, consumption of FAFH decreases not only because of an increase in its own price, but also because of strong cross-price effects from increases in other prices. Not surprisingly, the reduction in calories consumed under the fat tax also reflects a decrease in calories from both dairy and cereals and bakery products.

The magnitude of the deadweight loss under the two supply scenarios is approximately equivalent: $1,937 million when commodity supply is perfectly elastic and $1,717 million using the lower-bound estimates of supply elasticities. Public health care expenditures attributable to obesity would decline by approximately $3,612 million in the case of exogenous commodity prices, and $3,394 million using the lower-bound estimates of supply elasticities. These measures are statistically significantly different from zero, and the probability of a negative change in total welfare (including changes in public health care costs associated with changes in body weight) from a fat tax under all the supply regimes is essentially zero. The fat tax would ultimately save between $0.15 and $0.23 per pound of weight lost by adult Americans.

Calorie Tax. Suppose the U.S. government taxed food products at a rate of approximately $0.00016 per calorie to achieve approximately the same reduction in calories as the fat tax of $5 per kilogram. Again, more than half of the calorie reduction would be the result of a decrease in calories consumed from FAFH. However, unlike the fat tax, under a calorie tax about one-quarter of the total decrease in calories consumed per adult per year would result from reduced consumption of cereals and

[10] Since the social welfare measure is nonlinear in the tax rate used, we tested the sensitivity of our results to the choice of tax rates by estimating the changes in social welfare with various tax rates including $2.5 and $10 tax per kilogram of fat, and taxes on sugar, calories, and all food that generated approximately the same calorie reduction as the fat tax (see appendix tables A-2a, A-2b and A-3.). At a $2.5 tax per kilogram of fat, the tax rates required to achieve the same reduction in calorie consumption are roughly a $1.344 tax per kilogram of sugar, a $0.0001632 tax per calorie and a 2.5% uniform tax. At a $10 tax per kilogram of fat, the tax rates that would generate an equivalent reduction in calorie consumption are roughly a $5.376 tax per kilogram of sugar, a $0.00033 tax per calorie and a 10% uniform tax. Our findings are generally robust to the choice of tax rate except for the fat tax policy in the extreme case of doubling the tax rate, which resulted in a net social cost rather than a net social benefit. When the fat tax is doubled, the probability that the change in social welfare (including a provision for public health care costs associated with obesity) is greater than zero, is between 0.3 and 0.5 depending on the slope of commodity supply. Because the deadweight loss associated with tax collection is quadratic in t and the public health care costs are linear in t, as we increase the tax rate the measure of deadweight loss associated with a policy will eventually become greater than the savings associated with a reduction in public health care costs. In the case of the doubling of the fat tax, this is what occurred.

bakery products. Again, changes in the consumption of dairy products would contribute importantly to the reduction in consumption of calories (a reduction of 1,578 kcal per year using the lower-bound estimates of supply elasticities, or 1,500 kcal per year with perfectly elastic commodity supply), although the magnitude of the change is smaller compared with the fat tax.

Compared with the fat tax, the calorie tax would distort relative prices and consumption less, which implies a smaller deadweight loss. The deadweight loss from the calorie tax ranges between $1,102 million and $1,131 million per year, both statistically significantly different from zero. Because the tax rates under the different tax policies were constructed to achieve approximately the same reduction in calorie consumption per adult per year, the change in public health care expenditures is approximately the same under the calorie tax as it is under the fat tax. The change in social welfare, including changes in public health care expenditures, from the calorie tax is positive (between $1,262 million and $1,271 million per year), which reflects the smaller deadweight loss associated with the calorie tax compared with the fat tax. A calorie tax would cost $0.89 per pound lost for an American adult if we do not account for the resulting reduction in health care expenditures associated with decreases in obesity. Including these savings implies a benefit of $1.77 per pound lost under a calorie tax.

Sugar Tax. Suppose, alternatively, that the U.S. government taxed food products at a rate of $0.0026 per gram of sugar to achieve approximately the same reduction in calories as would the fat and calorie tax. Like the fat and calorie taxes, more than half of the reduction in calories consumed would reflect a decrease in calories consumed from FAFH. However, unlike taxes on fat or calories, a reduction in calories consumed from nonalcoholic beverages would account for about one-quarter of the total decrease in calories consumed per adult per year. Similar to the fat and calorie taxes, changes in the consumption of dairy products are an important source of calorie reduction (reductions of 2,280 kcal per adult per year using the lower-bound estimates of supply elasticities, compared with 3,114 kcal per adult per year under a perfectly elastic commodity supply). Compared with the fat and calorie taxes, the sugar tax would be associated with a deadweight loss of $1,330 million under exogenous commodity prices, and $1,251 million under an upward-sloping commodity supply. When the reduction in public health care expenditures associated with the calorie reduction is included, the change in social welfare becomes a net gain (between $2,169 and $2,232 million). Including the changes in health care costs from the sugar policy, the benefit would be between $1.67 and $1.73 per adult pound lost, which is smaller than the benefit from an equivalent calorie tax, but still better than the fat tax.

Uniform Food Tax. The last tax policy we analyze is a uniform tax on all foods at a rate of about 5%. The uniform tax rate was chosen to achieve approximately the same reduction in calories as the taxes on fat, calories, or sugar would, that is, around 18–19,000 kcal per adult per year. The uniform tax is more distortionary than the sugar and calorie taxes are, but less so than the fat tax. The deadweight loss excluding changes in health care costs induced by the uniform tax would be between $1,422 million and $1,587 per year. Like the calorie tax and sugar tax, the uniform tax could potentially result in a net gain if changes in public health care costs are considered. The uniform tax would benefit the United States by $1.28 per pound lost, in the case of upward sloping supply, or $1.54 per pound lost in the case of perfectly elastic supply.

Summary and Conclusion

Previous studies of the potential impacts of food and farm policies on obesity have imposed restrictive assumptions on their analysis. For example, studies of the potential impacts of food policies on obesity have all assumed that 100% of the incidence of a tax or subsidy would be borne by final consumers. A related issue is the determination of the relevant counterfactual alternative in policy analysis. Many of these studies evaluated the effect of a tax or subsidy on one group of foods (e.g., beverages or snack foods) without considering substitution effects on the consumption of foods not included in their analysis.

We set out to analyze and evaluate the effects of food and farm policies on food consumption, adult body weight, and social welfare in the United States. To address this goal, we developed an equilibrium displacement model that allows for multiple inter-related food products to be vertically linked to multiple inter-related farm commodities and marketing inputs. We established the structure of the equilibrium displacement model to make it possible to obtain corresponding approximations to exact money metric measures of welfare changes associated with policy changes. Moreover, we showed how the solutions of the equilibrium displacement model could be used to estimate the effects of any of the policies on social welfare and its distribution between consumers and producers.

The first set of policy experiments showed that eliminating farm subsidies–including direct subsidies on grains and indirect subsidies from trade barriers on dairy, sugar, and fruit and vegetable commodities–would have very limited impact on calorie consumption, and hence, obesity. Second, we found that for both supply scenarios, the most efficient policy would be a tax on food based on its caloric content. A tax of \$0.0165 per 1,000 calories would yield a net benefit to national welfare of \$2,280 million, or \$10 per adult, which is equivalent to about \$1.79 per pound of fat lost. An equivalent sugar tax would also yield a benefit under both supply scenarios, although less than the calorie tax. A comparable fat tax or uniform food tax would entail larger deadweight losses but may still yield net social benefits, once the changes in public health care costs associated with changes in body weight are taken into account.

In contrast to the tax policies, the fruit and vegetable subsidies would be very inefficient. A 10% subsidy on fruit and vegetable retail products would cost \$20.14 per pound lost under the assumption of inelastic supply of commodities. Because the fruit and vegetable commodity subsidy would actually increase the consumption of calories under both supply scenarios, for comparison, we calculated the cost per pound of fat reduction for a 17% tax on fruit and vegetable commodities; a tax on fruit and vegetable commodities would be more efficient than a subsidy on fruit and vegetable retail products.

Ultimately, if the goal of policy-makers is simply to reduce obesity in the United States, the most efficient policy among those considered here would be to tax calories. If other objectives also matter, a more complex policy may be called for. For instance, particular foods might involve externalities other than through their impacts on obesity (e.g. the consumption of saturated fats may be implicated in cancers or coronary heart disease in ways that mean calories consumed as saturated fats should be taxed more heavily than calories generally). Conversely, the overall nutritional composition of an individual's diet, and not just the caloric content, may have health implications that matter (a diet of only grapefruit, which is low in calories, would be nutritionally poor), but would not be addressed by a calorie tax. Finally, a calorie tax would be regressive, falling disproportionately heavily on the poor. Consideration of these complications need not rule out a calorie tax, and it does not seem likely to change the efficiency ranking of a calorie tax relative to the other taxes and subsidies considered here. However, it does imply that a calorie tax might have to be implemented as part of a package, together with other instruments such as education programs, product information, and food assistance programs, and possibly combined with other taxes, subsidies, and regulations. The design of such policies might also need to account for the potential role of induced innovation in the food industry, which would make endogenous the nutrient content of particular food groups that has been treated as fixed in our analysis and is a dimension with significant potential for change.

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Technical Appendix of Derivations of Social Welfare Formula

The formula for social welfare (equation (34)) is derived by first solving the gradient of the social welfare function and then the Hessian of the social welfare function in (33). We first rewrite the $2(N+L)\times 1$ gradient of the social welfare function as:

$$\text{(1A-1)}\quad \nabla \mathrm{SW}(\mathbf{P},\mathbf{W},u)=\begin{bmatrix}\nabla_{P^D}\mathrm{SW}(\cdot)\\ \nabla_{P^S}\mathrm{SW}(\cdot)\\ \nabla_{W_D}\mathrm{SW}(\cdot)\\ \nabla_{W_S}\mathrm{SW}(\cdot)\end{bmatrix},$$

where ∇_{P^D} and ∇_{P^S} denote the vector of $N\times 1$ first-order partial derivatives of the social welfare function with respect to consumer and producer retail prices, and ∇_{W_D} and ∇_{W_S} denote the vector of $L\times 1$ first-order partial derivatives of the social welfare function with respect to buyer and seller commodity prices. The gradient of the social welfare function at $(\mathbf{P}^{(0)},\mathbf{W}^{(0)})$ is:

$$\text{(1A-2)}\quad \nabla \mathrm{SW}(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})$$
$$=\begin{bmatrix}\nabla_{P^D}\mathrm{g}(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})-\nabla_{P^D}\mathrm{e}(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})\\ \nabla_{P^S}\mathrm{g}(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})-\nabla_{P^S}\mathrm{e}(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})\\ \nabla_{W_D}\pi(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})+\nabla_{W_D}\mathrm{g}(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})\\ \nabla_{W_S}\pi(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})+\nabla_{W_S}\mathrm{g}(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})\end{bmatrix},$$

where $\nabla_{P^D}\mathrm{e}(\cdot)$, $\nabla_{P^D}\mathrm{g}(\cdot)$, $\nabla_{P^S}\mathrm{e}(\cdot)$, and $\nabla_{P^S}\mathrm{g}(\cdot)$ are $N\times 1$ gradients of the consumer expenditure and the government revenue functions, respectively, and $\nabla_{W_D}\pi(\cdot)$, $\nabla_{W_D}\mathrm{g}(\cdot)$ $\nabla_{W_S}\pi(\cdot)$ and $\nabla_{W_S}\mathrm{g}(\cdot)$ are $L\times 1$ gradients of the profit and government revenue functions with respect to consumer and product prices of commodities, respectively.

Several substitutions can be made to simplify (1A-2). Since the producer prices of retail products have no effect on the consumer expenditure on goods and the buyer prices of commodities have no effect on profits for commodity producers:

$$\text{(1A-3)}\quad \nabla_{P^S}\mathrm{e}(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})=0,$$

$$\text{(1A-4)}\quad \nabla_{W_D}\pi(\mathbf{P}^{(0)},\mathbf{W}^{(0)},u^{(0)})=0.$$

Second, Shephard's lemma implies that the derivative of the consumer expenditure function with respect to price n is the Hicksian demand for good n. Hence, the gradient of the consumer expenditure function with respect to consumer prices of retail products is an N-vector of Hicksian demands for retail products, $\mathrm{h}(\cdot):\nabla_{P^D}\mathrm{e}(\mathbf{P}^{(0)},u^{(0)})=\mathbf{h}(\mathbf{P}^{(0)},u^{(0)})$. At $(\mathbf{P}^{(0)},\mathbf{W}^{(0)})$, Hicksian demands for retail products are equal to their Marshallian counterparts, so:

$$\text{(1A-5)}\quad \nabla_{P^D}\mathrm{e}(\mathbf{P}^{(0)},u^{(0)})=\mathbf{Q}^{(0)}.$$

Third, Hotelling's lemma implies that the partial derivative of the profit function with respect to the producer price of commodity l is the supply of commodity l. Hence, stacking the L partial derivatives into an $L \times 1$ vector yields the gradient of the profit function, which is equal to an $L \times 1$ vector of commodity supplies, commodity demands at $(\mathbf{P}^{(0)}, \mathbf{W}^{(0)})$:

$$\text{(1A-6)} \quad \nabla_{W_S} \pi(\mathbf{W}^{(0)}) = \mathbf{X}^{(0)}.$$

After substituting (1A-3)–(1A-6) into (1A-2), the gradient of the social welfare becomes:

$$\text{(1A-7)} \quad \nabla \mathrm{SW}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) = \begin{bmatrix} \nabla_{P^D} \mathrm{g}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) - \mathbf{Q}^{(0)} \\ \nabla_{P^S} \mathrm{g}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) \\ \nabla_{W_D} \mathrm{g}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) \\ \mathbf{X}^{(0)} + \nabla_{W_S} \mathrm{g}(\mathbf{P}^{(0)}, \mathbf{W}^{(0)}, u^{(0)}) \end{bmatrix}.$$

The $2(N + L) \times 2(N + L)$ Hessian of the social welfare function is:

$$\text{(1A-8)} \quad \nabla^2 \mathrm{SW}(\cdot) = \begin{bmatrix} \nabla^2_{PD} \mathrm{SW}(\cdot) & \nabla_{PD\,PS} \mathrm{SW}(\cdot) & \mathbf{0} & \mathbf{0} \\ \nabla_{PS\,PD} \mathrm{SW}(\cdot) & \nabla^2_{PS} \mathrm{SW}(\cdot) & \mathbf{0} & \mathbf{0} \\ \mathbf{0}^{\mathrm{T}} & \mathbf{0}^{\mathrm{T}} & \nabla^2_{W_D} \mathrm{SW}(\cdot) & \nabla_{W_D W_S} \mathrm{SW}(\cdot) \\ \mathbf{0}^{\mathrm{T}} & \mathbf{0}^{\mathrm{T}} & \nabla_{W_S W_D} \mathrm{SW}(\cdot) & \nabla^2_{W_S} \mathrm{SW}(\cdot) \end{bmatrix},$$

where $\mathbf{0}$ is a $N \times L$ matrix of zeros, $\nabla^2_{P^D}$, $\nabla^2_{PS} \nabla_{P^D P^S}$ and $\nabla_{P^S P^D}$ denote the $N \times N$ second-order partial derivatives of the social welfare function with respect to consumer and producer retail prices, and $\nabla^2_{W_D}$, $\nabla^2_{W_S} \nabla_{W_D W_S}$ and $\nabla_{W_S W_D}$ denote the vector of $L \times L$ second-order partial derivatives of the social welfare function with respect to buyer and seller commodity prices. The Hessian of the social welfare function can be rewritten as:

$$\text{(1A-9)} \quad \nabla^2 \mathrm{SW}(\cdot) = \begin{bmatrix} \nabla^2_{P^D} \mathrm{g}(\cdot) - \nabla^2_{P^D} \mathrm{e}(\cdot) & \nabla_{P^D P^S} \mathrm{g}(\cdot) & \mathbf{0} & \mathbf{0} \\ \nabla_{P^S P^D} \mathrm{g}(\cdot) & \nabla^2_{P^S} \mathrm{g}(\cdot) & \mathbf{0} & \mathbf{0} \\ \mathbf{0}^{\mathrm{T}} & \mathbf{0}^{\mathrm{T}} & \nabla^2_{W_D} \mathrm{g}(\cdot) & \nabla_{W_D W_S} \mathrm{g}(\cdot) \\ \mathbf{0}^{\mathrm{T}} & \mathbf{0}^{\mathrm{T}} & \nabla_{W_S W_D} \mathrm{g}(\cdot) & \nabla^2_{W_S} \pi(\cdot) + \nabla^2_{W_S} \mathrm{g}(\cdot) \end{bmatrix}$$

Several substitutions can be made to simplify (1A-9). First, the Hessian of the expenditure function with respect to consumer prices is the $N \times N$ Slutsky matrix, $\mathbf{S}(\mathbf{P}^{(0)}, u^{(0)})$:

$$\text{(1A-10)} \quad \nabla^2_{P^D} \mathrm{e}(\mathbf{P}^{(0)}, u^{(0)}) = \nabla_{P^D} \mathbf{h}(\mathbf{P}^{(0)}, u^{(0)}) = \mathbf{S}(\mathbf{P}^{(0)}, u^{(0)}).$$

Second, Hotelling's lemma implies:

$$\text{(1A-11)} \quad \nabla^2_{W^S} \pi(\mathbf{W}^{(0)}) = \nabla_{W^S} \mathbf{X}_S(\mathbf{W}^{(0)}, \boldsymbol{\beta}^{(0)}),$$

where $\nabla_{W^S} \mathbf{X}_S(\mathbf{W}^{(0)}, \boldsymbol{\beta}^{(0)})$ is an $L \times L$ matrix of partial derivatives of commodity demands with respect to commodity prices. Substituting (1A-10) and (1A-11) into (1A-9), the Hessian of the social welfare function becomes:

$$\text{(1A-12)} \quad \nabla^2 \mathrm{SW}(\cdot) = \begin{bmatrix} \nabla^2_{PD} \mathrm{g}(\cdot) - \mathbf{S}(\cdot) & \nabla_{PD\,PS} \mathrm{g}(\cdot) & \mathbf{0} & \mathbf{0} \\ \nabla_{PS\,PD} \mathrm{g}(\cdot) & \nabla^2_{PS} \mathrm{g}(\cdot) & \mathbf{0} & \mathbf{0} \\ \mathbf{0}^{\mathrm{T}} & \mathbf{0}^{\mathrm{T}} & \nabla^2_{W_D} \mathrm{g}(\cdot) & \nabla_{W_D W_S} \mathrm{g}(\cdot) \\ \mathbf{0}^{\mathrm{T}} & \mathbf{0}^{\mathrm{T}} & \nabla_{W_S W_D} \mathrm{g}(\cdot) & \nabla_{W_S} \mathbf{X}(\cdot) + \nabla^2_{W_S} \mathrm{g}(\cdot) \end{bmatrix}.$$

The change in social welfare from a policy-induced price change is found by substituting (1A-7) and (1A-12) into (1A-2) and multiplying out the block matrices:

$$\begin{aligned} \text{(1A-13)} \quad \Delta SW \approx{} & \left(\Delta \mathbf{P}^D\right)^{\mathrm{T}} \left[\nabla_{P^D} \mathrm{g}(\cdot) - \mathbf{Q}^{(0)}\right] \\ & + \left(\Delta \mathbf{P}^S\right)^{\mathrm{T}} \nabla_{P^S} \mathrm{g}(\cdot) \\ & + (\Delta \mathbf{W}_S)^{\mathrm{T}} \left[\mathbf{X}^{(0)} + \nabla_{W_S} \mathrm{g}(\cdot)\right] \\ & + (\Delta \mathbf{W}_D)^{\mathrm{T}} \nabla_{W_D} \mathrm{g}(\cdot) \\ & + 0.5 \Big[\left(\Delta \mathbf{P}^D\right)^{\mathrm{T}} \left(\nabla^2_{P^D} \mathrm{g}(\cdot) - \mathbf{S}(\cdot)\right) \\ & + \left(\Delta \mathbf{P}^S\right)^{\mathrm{T}} \nabla_{P^S P^D} \mathrm{g}(\cdot)\Big] \Delta \mathbf{P}^D \\ & + 0.5 \Big[\left(\Delta \mathbf{P}^D\right)^{\mathrm{T}} \nabla_{P^D P^S} \mathrm{g}(\cdot) \\ & + \left(\Delta \mathbf{P}^S\right)^{\mathrm{T}} \nabla^2_{P^S} \mathrm{g}(\cdot)\Big] \Delta \mathbf{P}^S \\ & + 0.5 \left[(\Delta \mathbf{W}_S)^{\mathrm{T}} \nabla_{W_S W_D} \mathrm{g}(\cdot) \right. \\ & \left. + (\Delta \mathbf{W}_D)^{\mathrm{T}} \nabla^2_{W_D} \mathrm{g}(\cdot)\right] \Delta \mathbf{W}_D \\ & + 0.5 \left[(\Delta \mathbf{W}_S)^{\mathrm{T}} (\nabla_{W_S} \mathbf{X}(\cdot) \right. \\ & + \nabla^2_{W_S} \mathrm{g}(\cdot)) \\ & \left. + (\Delta \mathbf{W}_D)^{\mathrm{T}} \nabla_{W_D W_S} \mathrm{g}(\cdot)\right] \Delta \mathbf{W}_S. \end{aligned}$$

Letting $\mathbf{I}^P$ and $\mathbf{I}^Q$ be $N \times N$ identity matrices with diagonal elements $P^{n(0)}/P^{n(0)}, \forall n = 1, \ldots, N$, and $Q^{n(0)}/Q^{n(0)}, \forall n = 1, \ldots, N$, respectively, and $\mathbf{I}_W$ and $\mathbf{I}_X$ be $L \times L$ identity matrices with diagonal elements, $W_l^{(0)}/W_l^{(0)}, \forall l = 1, \ldots, L$ and $X_l^{(0)}/X_l^{(0)}, \forall l = 1, \ldots, L$, respectively, (1A-13) can be rewritten as:

(1A-14)

$$\begin{aligned}\Delta SW \approx & \left(\Delta \mathbf{P}^{D}\right)^{\mathrm{T}} \mathbf{I}^{P}\left[\nabla_{P^{D}}(\cdot)-\mathbf{Q}^{(0)}\right] \\ & +\left(\Delta \mathbf{P}^{S}\right)^{\mathrm{T}} \mathbf{I}^{P} \nabla_{P^{S}} \mathrm{g}(\cdot) \\ & +(\Delta \mathbf{W}_{S})^{\mathrm{T}} \mathbf{I}_{W}\left[\mathbf{X}^{(0)}+\nabla_{W_{S}} \mathrm{g}(\cdot)\right] \\ & +(\Delta \mathbf{W}_{D})^{\mathrm{T}} \mathbf{I}_{W} \nabla_{W_{D}} \mathrm{g}(\cdot) \\ & +0.5\left[\left(\Delta \mathbf{P}^{D}\right)^{\mathrm{T}} \mathbf{I}^{P}\left(\nabla_{P^{D}}^{2} \mathrm{g}(\cdot)-\mathbf{I}^{Q} \mathbf{S}(\cdot)\right)\right. \\ & \left.+\left(\Delta \mathbf{P}^{S}\right)^{\mathrm{T}} \mathbf{I}^{P} \nabla_{P^{S} P^{D}} \mathrm{g}(\cdot)\right] \mathbf{I}^{P} \Delta \mathbf{P}^{D} \\ & +0.5\left[\left(\Delta \mathbf{P}^{D}\right)^{\mathrm{T}} \mathbf{I}^{P} \nabla_{P^{D} P^{S}} \mathrm{g}(\cdot)\right. \\ & \left.+\left(\Delta \mathbf{P}^{S}\right)^{\mathrm{T}} \mathbf{I}^{P} \nabla_{P^{S}}^{2} \mathrm{g}(\cdot)\right] \mathbf{I}^{P} \Delta \mathbf{P}^{S} \\ & +0.5\left[(\Delta \mathbf{W}_{S})^{\mathrm{T}} \mathbf{I}_{W} \nabla_{W_{S} W_{D}} \mathrm{g}(\cdot)\right. \\ & \left.+(\Delta \mathbf{W}_{D})^{\mathrm{T}} \mathbf{I}_{W} \nabla_{W_{D}}^{2} \mathrm{g}(\cdot)\right] \mathbf{I}_{W} \Delta \mathbf{W}_{D} \\ & +0.5\left[(\Delta \mathbf{W}_{S})^{\mathrm{T}} \mathbf{I}_{W}\left(\mathbf{I}_{X} \nabla_{W_{S}} \mathbf{X}(\cdot)\right.\right. \\ & \left.+\nabla_{W_{S}}^{2} \mathrm{g}(\cdot)\right) \\ & \left.+(\Delta \mathbf{W}_{D})^{\mathrm{T}} \mathbf{I}_{W} \nabla_{W_{D} W_{S}} \mathrm{g}(\cdot)\right] \mathbf{I}_{W} \Delta \mathbf{W}_{S}.\end{aligned}$$

When the identity matrices are multiplied through (1A-14), the vectors of price differences are transformed into proportionate changes in prices, $\mathbf{EP}^{D}$, $\mathbf{EP}^{S}$, $\mathbf{EW}_{D}$, and $\mathbf{EW}_{S}$ and $\nabla_{W_S}\mathbf{X}(\cdot)$ and $\mathbf{S}(\cdot)$ are transformed into matrices of elasticities:

(1A-15)

$$\begin{aligned}\Delta SW \approx & \left(\mathbf{EP}^{D}\right)^{\mathrm{T}} \mathbf{D}^{P}\left[\nabla_{P^{D}} \mathrm{g}(\cdot)-\mathbf{Q}^{(0)}\right] \\ & +\left(\mathbf{EP}^{S}\right)^{\mathrm{T}} \mathbf{D}^{P} \nabla_{P^{S}} \mathrm{g}(\cdot) \\ & +(\mathbf{EW}_{S})^{\mathrm{T}} \mathbf{D}_{W}\left[\mathbf{X}^{(0)}+\nabla_{W_{S}} \mathrm{g}(\cdot)\right] \\ & +(\mathbf{EW}_{D})^{\mathrm{T}} \mathbf{D}_{W} \nabla_{W_{D}} \mathrm{g}(\cdot) \\ & -0.5\left[\left(\mathbf{EP}^{D}\right)^{\mathrm{T}} \mathbf{D}^{PQ} \boldsymbol{\eta}^{*N}\right] \mathbf{EP}^{D} \\ & +0.5\left[\left(\mathbf{EP}^{D}\right)^{\mathrm{T}} \mathbf{D}^{P} \nabla_{P^{D}}^{2} \mathrm{g}(\cdot) \mathbf{D}^{P}\right. \\ & \left.+\left(\mathbf{EP}^{S}\right)^{\mathrm{T}} \mathbf{D}^{P} \nabla_{P^{S} P^{D}} \mathrm{g}(\cdot) \mathbf{D}^{P}\right] \mathbf{EP}^{D} \\ & +0.5\left[\left(\mathbf{EP}^{D}\right)^{\mathrm{T}} \mathbf{D}^{P} \nabla_{P^{D} P^{S}} \mathrm{g}(\cdot)\right. \\ & \left.+\left(\mathbf{EP}^{S}\right)^{\mathrm{T}} \mathbf{D}^{P} \nabla_{P^{S}}^{2} \mathrm{g}(\cdot)\right] \mathbf{D}^{P} \mathbf{EP}^{S} \\ & +0.5\left[(\mathbf{EW}_{S})^{\mathrm{T}} \mathbf{D}_{W} \nabla_{W_{S} W_{D}} \mathrm{g}(\cdot)\right. \\ & \left.+(\mathbf{EW}_{D})^{\mathrm{T}} \mathbf{D}_{W} \nabla_{W_{D}}^{2} \mathrm{g}(\cdot)\right] \mathbf{D}_{W} \mathbf{EW}_{D} \\ & +0.5\left[(\mathbf{EW}_{S})^{\mathrm{T}} \mathbf{D}_{WX} \boldsymbol{\varepsilon}_{L}\right] \mathbf{EW}_{S} \\ & +0.5\left[(\mathbf{EW}_{S})^{\mathrm{T}} \mathbf{D}_{W} \nabla_{W_{S}}^{2} \mathrm{g}(\cdot) \mathbf{D}_{W}\right. \\ & \left.+(\mathbf{EW}_{D})^{\mathrm{T}} \mathbf{D}_{W} \nabla_{W_{D} W_{S}} \mathrm{g}(\cdot) \mathbf{D}_{W}\right] \mathbf{EW}_{S},\end{aligned}$$

where $\mathbf{D}^{P}$ and $\mathbf{D}^{Q}$ are $N \times N$ diagonal matrices where the diagonal elements are $P^{n(0)}, \forall n=1,\ldots,N$ and $Q^{n(0)}, \forall n=1,\ldots,N$, respectively, $\mathbf{D}_W$ and $\mathbf{D}_X$ are $L \times L$ diagonal matrices where the diagonal elements are $W_l^{(0)}, \forall l=1,\ldots,L$ and $X_l^{(0)}, l=1,\ldots,L$, respectively, $\boldsymbol{\eta}^{N*}$ is an $N \times N$ matrix of Hicksian elasticities of demand for retail products and $\boldsymbol{\varepsilon}_L$ is an $L \times L$ matrix of elasticities of supply of commodities. Using the Slutsky equation, (1A-15) can be modified as:

(1A-16)

$$\begin{aligned}\Delta SW \approx\ & (\mathbf{EW}_{S})^{\mathrm{T}}\mathbf{D}_{W}\mathbf{X}^{(0)} \\ & +0.5(\mathbf{EW}_{S})^{\mathrm{T}}\mathbf{D}_{WX}\boldsymbol{\varepsilon}_{L}\mathbf{EW}_{S} && \text{(a)} \\ & -[(\mathbf{EP}^{D})^{\mathrm{T}}\mathbf{D}^{P}\mathbf{Q}^{(0)}+0.5(\mathbf{EP}^{D})^{\mathrm{T}} && \text{(b)} \\ & \times\mathbf{D}^{PQ}(\boldsymbol{\eta}^{N}+\boldsymbol{\eta}^{N,M}\mathbf{w}^{\mathrm{T}})\mathbf{EP}^{D}] && \text{(c)} \\ & +(\mathbf{EP}^{D})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{D}}\mathrm{g}(\cdot)+(\mathbf{EP}^{S})^{\mathrm{T}} && \text{(d)} \\ & \times\mathbf{D}^{P}\nabla_{P^{S}}\mathrm{g}(\cdot) && \text{(e)} \\ & +0.5(\mathbf{EP}^{D})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{D}}^{2}\mathrm{g}(\cdot)\mathbf{D}^{P}\mathbf{EP}^{D} && \text{(f)} \\ & +0.5(\mathbf{EP}^{S})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{S}}^{2}\mathrm{g}(\cdot)\mathbf{D}^{P}\mathbf{EP}^{S} && \text{(g)} \\ & +0.5(\mathbf{EP}^{D})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{D}P^{S}}\mathrm{g}(\cdot)\mathbf{D}^{P}\mathbf{EP}^{S} && \text{(h)} \\ & +0.5(\mathbf{EP}^{S})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{S}P^{D}}\mathrm{g}(\cdot)\mathbf{D}^{P}\mathbf{EP}^{D} && \text{(i)} \\ & +(\mathbf{EW}_{S})^{\mathrm{T}}\mathbf{D}_{W}\nabla_{W_{S}}\mathrm{g}(\cdot)+(\mathbf{EW}_{D})^{\mathrm{T}} && \text{(j)} \\ & \times\mathbf{D}_{W}\nabla_{W_{D}}\mathrm{g}(\cdot) && \text{(k)} \\ & +0.5(\mathbf{EW}_{D})^{\mathrm{T}}\mathbf{D}_{W}\nabla_{W_{D}}^{2}\mathrm{g}(\cdot) && \text{(l)} \\ & \times\mathbf{D}_{W}\mathbf{EW}_{D} && \text{(m)} \\ & +0.5(\mathbf{EW}_{S})^{\mathrm{T}}\mathbf{D}_{W}\nabla_{W_{S}}^{2}\mathrm{g}(\cdot) && \text{(n)} \\ & \times\mathbf{D}_{W}\mathbf{EW}_{S} && \text{(o)} \\ & +0.5(\mathbf{EW}_{D})^{\mathrm{T}}\mathbf{D}_{W}\nabla_{W_{D}W_{S}}\mathrm{g}(\cdot) && \text{(p)} \\ & \times\mathbf{D}_{W}\mathbf{EW}_{S} && \text{(q)} \\ & +0.5(\mathbf{EW}_{S})^{\mathrm{T}}\mathbf{D}_{W}\nabla_{W_{S}W_{D}}\mathrm{g}(\cdot) && \text{(r)} \\ & \times\mathbf{D}_{W}\mathbf{EW}_{D}, && \text{(s)}\end{aligned}$$

where $\boldsymbol{\eta}^{N}$ is an $N \times N$ matrix of Marshallian elasticities of demand for retail products with respect to retail price, $\boldsymbol{\eta}^{N,M}$ is an $N \times 1$ vector of elasticities of demand with respect to total expenditure, and $\mathbf{w}$ is an $N \times 1$ vector of consumer budget shares.

Now we must find the first- and second-order partial derivatives of the government revenue function with respect to all prices. The government can generate revenue by taxing commodities, retail products, or both. The government revenue generated from taxing J (M) retail product (commodity) markets is the sum of the differences between the producer (seller) price, P^{Sj} (W_{Sj}), and the consumer (buyer) price, $P^{Dj}(W_{Dj})$ times the corresponding quantity sold in the taxed market, Q^j (X_j):

(1A-17)

$$g(\mathbf{P},\mathbf{W}) = \sum_{j=1}^{J}(P^{Dj} - P^{Sj})Q^j + \sum_{m=1}^{M}(W_{Dm} - W_{Sm})X_m.$$

For brevity, we show the calculations for the case of a retail tax policy but the effects of a commodity tax policy on government revenue are symmetric to those of a retail tax policy. The first-order partial derivatives of the government revenue function with respect to all the prices are:

(1A-18)

$$\frac{\partial g(\mathbf{P},\mathbf{W})}{\partial P^{Dj}} = Q^j + \sum_{l=1}^{J}(P^{Dl} - P^{Sl})\frac{\partial Q^l}{\partial P^{Dj}}, \quad \forall j = 1,\ldots,J,$$

(1A-19)

$$\frac{\partial g(\mathbf{P},\mathbf{W})}{\partial P^{Sj}} = -Q^j + \sum_{l=1}^{J}(P^{Dl} - P^{Sl})\frac{\partial Q^l}{\partial P^{Sj}}, \quad \forall j = 1,\ldots,J.$$

Note that when (1A-18)–(1A-19) are evaluated at $\mathbf{P}^{(0)}$, the second term on the RHS is zero in both equations. Hence, substituting $\nabla_{P^D}g(\cdot)$ and $\nabla_{P^S}g(\cdot)$ into (1A-16) and expressing the results in summation notation yields the following equations for the first-order effects of a retail tax policy on government revenue:

(1A-20)

$$(\mathbf{EP}^D)^{\mathrm{T}}\mathbf{D}^P\nabla_{P^D}g(\cdot) = \sum_{n}^{N}\delta^n EP^{Dn}P^{n(0)}Q^{n(0)}$$

(1A-21)

$$(\mathbf{EP}^S)^{\mathrm{T}}\mathbf{D}^P\nabla_{P^S}g(\cdot) = -\sum_{n}^{N}\delta^n EP^{Sn}P^{n(0)}Q^{n(0)},$$

where $\delta^j = \begin{cases} 1 & \text{if } t^j > 0 \\ 0 & \text{otherwise} \end{cases}, \forall j = 1,\ldots,N.$

The second-order partial derivatives of the government revenue function are:

(1A-22)

$$\frac{\partial^2 g(\mathbf{P},\mathbf{W})}{\partial P^{Dj}\partial P^{Dk}} = \frac{\partial Q^j(\cdot)}{\partial P^{Dk}} + \frac{\partial Q^k(\cdot)}{\partial P^{Dj}} + \sum_{l=1}^{J}(P^{Dl} - P^{Sl})\frac{\partial^2 Q^l}{\partial P^{Dj}\partial P^{Dk}}, \quad \forall k,j = 1,\ldots,J,$$

(1A-23)

$$\frac{\partial^2 g(\mathbf{P},\mathbf{W})}{\partial P^{Sj}\partial P^{Sk}} = -\left(\frac{\partial Q^j(\cdot)}{\partial P^{Sk}} + \frac{\partial Q^k(\cdot)}{\partial P^{Sj}}\right) + \sum_{l=1}^{J}(P^{Dl} - P^{Sl})\frac{\partial^2 Q^l}{\partial P^{Sj}\partial P^{Sk}}, \quad \forall k,j = 1,\ldots,J,$$

(1A-24)

$$\frac{\partial^2 g(\mathbf{P},\mathbf{W})}{\partial P^{Dj}\partial P^{Sk}} = \frac{\partial Q^j(\cdot)}{\partial P^{Sk}} - \frac{\partial Q^k(\cdot)}{\partial P^{Dj}} + \sum_{l=1}^{J}(P^{Dl} - P^{Sl})\frac{\partial^2 Q^l}{\partial P^{Dj}\partial P^{Sk}}, \quad \forall k,j = 1,\ldots,J,$$

(1A-25)

$$\frac{\partial^2 g(\mathbf{P},\mathbf{W})}{\partial P^{Sj}\partial P^{Dk}} = \frac{\partial Q^j(\cdot)}{\partial P^{Dk}} - \frac{\partial Q^k(\cdot)}{\partial P^{Sj}} + \sum_{l=1}^{J}(P^{Dl} - P^{Sl})\frac{\partial^2 Q^l}{\partial P^{Sj}\partial P^{Dk}}, \quad \forall k,j = 1,\ldots,J.$$

Again, note that when (1A-22)–(1A-25) are evaluated at $\mathbf{P}^{(0)}$, the third term on the RHS is zero in these equations. Evaluating (1A-22)–(1A-25) at $\mathbf{P}^{(0)}$, and substituting $\nabla^2_{P^D}g(\cdot)$, $\nabla^2_{P^S}g(\cdot)$, $\nabla_{P^DP^S}g(\cdot)$, and $\nabla_{P^SP^D}g(\cdot)$ into lines (f) – (i) in (1A-16) gives

(1A-26)

$$(\mathbf{EP}^D)^{\mathrm{T}}\mathbf{D}^P\nabla^2_{P^D}g(\cdot)\mathbf{D}^P\mathbf{EP}^D$$

$$= 2\sum_{n}^{N}\sum_{j}^{N}\delta^{j}EP^{Dj}P^{j(0)}Q^{j(0)}\eta^{jn}EP^{Dn},$$

(1A-27)
$$(\mathbf{EP}^{S})^{\mathrm{T}}\mathbf{D}^{P}\nabla^{2}_{P^{S}}g(\cdot)\mathbf{D}^{P}\mathbf{EP}^{S}$$
$$= -2\sum_{n}^{N}\sum_{j}^{N}\delta^{j}EP^{Sj}P^{j(0)}Q^{j(0)}\varepsilon^{jn}EP^{Sn},$$

(1A-28)
$$(\mathbf{EP}^{D})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{D}P^{S}}g(\cdot)\mathbf{D}^{P}\mathbf{EP}^{S}$$
$$= \sum_{n}^{N}\sum_{j}^{N}\delta^{j}EP^{Sj}P^{j(0)}Q^{j(0)}\eta^{jn}EP^{Dn}$$
$$- \sum_{n}^{N}\sum_{j}^{N}\delta^{j}EP^{Dn}P^{n(0)}Q^{n(0)}\varepsilon^{nj}EP^{Sn},$$

(1A-29)
$$(\mathbf{EP}^{S})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{S}P^{D}}g(\cdot)\mathbf{D}^{P}\mathbf{EP}^{D}$$
$$= -\sum_{n}^{N}\sum_{j}^{N}\delta^{j}EP^{Sj}P^{j(0)}Q^{j(0)}\eta^{jn}EP^{Dn}$$
$$+ \sum_{n}^{N}\sum_{j}^{N}\delta^{j}EP^{Dn}P^{n(0)}Q^{n(0)}\varepsilon^{nj}EP^{Sn}.$$

After (1A-20), (1A-21) and (1A-26)–(1A-29) are substituted into lines (d)–(i) in (1A-16), noting that equations (1A-28) and (1A-29) cancel each other out, the change in government revenue from a retail tax policy can be expressed as:

(1A-30)

$$\Delta g | t^{N} > 0$$
$$= (\mathbf{EP}^{D})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{D}}g(\cdot) + (\mathbf{EP}^{S})^{\mathrm{T}}\mathbf{D}^{P}\nabla_{P^{S}}g(\cdot)$$
$$+ 0.5(\mathbf{EP}^{D})^{\mathrm{T}}\mathbf{D}^{P}\nabla^{2}_{P^{D}}g(\cdot)\mathbf{D}^{P}\mathbf{EP}^{D}$$
$$+ 0.5(\mathbf{EP}^{S})^{\mathrm{T}}\mathbf{D}^{P}\nabla^{2}_{P^{S}}g(\cdot)\mathbf{D}^{P}\mathbf{EP}^{S}$$
$$= \sum_{n}^{N}\delta^{n}Q^{n(0)}P^{n(0)}(EP^{Dn} - EP^{Sn})$$
$$+ \sum_{n}^{N}\delta^{n}Q^{n(0)}P^{n(0)}EP^{Dn}\sum_{j}^{N}\eta^{nj}EP^{Dj}$$
$$+ \sum_{n}^{N}\delta^{n}Q^{n(0)}P^{n(0)}EP^{Sn}\sum_{j}^{N}\varepsilon^{nj}EP^{Sj}.$$

Because $EQ^{n} = \sum_{j}^{N}\eta^{nj}EP^{Dj}, EQ^{n} = \sum_{j}^{N}\varepsilon^{nj}EP^{Sj}$, and $t^{n} = EP^{Dn} - EP^{Sn}$, this equation can be more succinctly written as:

$$\text{(1A-31)}\quad \Delta g = \sum_{n}^{N}t^{n}Q^{n(0)}P^{n(0)}(1 + EQ^{n}).$$

Symmetrically, the change in government revenue from a tax or subsidy policy on commodities can be expressed as:

(1A-32)
$$\Delta g = -\sum_{l}^{L}s_{l}X_{l}^{(0)}W_{l}^{(0)}$$
$$- \sum_{l}^{L}s_{l}X_{l}^{(0)}W_{l}^{(0)}EX_{l}.$$

In matrix notation, equations (1A-31) and (1A-32) can be rewritten as:

(1A-33)
$$\Delta g = (\mathbf{t}^{N})^{\mathrm{T}}\mathbf{D}_{P}\mathbf{Q} + (\mathbf{t}^{N})^{\mathrm{T}}\mathbf{D}_{PQ}\mathbf{EQ},$$
(1A-34)
$$\Delta g = -(\mathbf{s}_{L})^{\mathrm{T}}\mathbf{D}_{W}\mathbf{X} - (\mathbf{s}_{L})^{\mathrm{T}}\mathbf{D}_{WX}\mathbf{EX},$$

where $\mathbf{D}_{W}\mathbf{X}$ and $\mathbf{D}^{P}\mathbf{Q}$ are $L \times 1$ and $N \times 1$ vectors of total expenditures on commodities and products, respectively.

Technical Appendix: Derivation of Ad Valorem Taxes on Foods

We derived ad valorem taxes for foods that would correspond to per unit taxes on their content of fat, calories, or sugar. First, we calculated the nutrient content of a pound of each food measured as calories, fat grams or sugar grams per pound using one day of dietary recall data from the 2003-04 National Health and Nutrition Examination Survey (column (3) in table A-1). The per unit tax per pound of each food category is equal to the per unit tax per calorie, gram of fat, or gram of sugar, multiplied by the fat, sugar, or calorie intensity of that food (column (4)) (i.e. calorie intensity is calories per pound of food consumed, and sugar and fat intensity are grams of sugar or fat per pound of food consumed). The average unit value for each food category in 2005 is calculated as personal consumption expenditures per adult per day from the National Income and Product Accounts (U.S. Department of Commerce, Bureau of Economic Analysis 2010) divided by the average number of pounds of food in that category consumed per day per adult (column (6)). The ad valorem tax rate is the tax rate in dollars per pound in column (4) divided by the unit values in dollars per pound in column (6).

Table A-1. Derivations of Ad Valorem Taxes on Food Based on a Per Unit Tax Per Gram of Fat, Per Gram of Sugar, and Per Calorie

	Sources of Fat/ Sugar/Calories (1)	Weight of Foods (2)	Fat/Sugar/Calorie Intensity of Food (3) = (1)/(2)	Per Unit Tax Per Pound of Food (4) = t × (3)	Expenditure on Food (2002$) (5)	Average Unit Value of Food (6) = (5)/(2)	Ad Valorem Tax (7) = (4)/(6) × 100
					t = $0.005 Tax per Gram of Fat		
	grams/day	*lbs/day*	*grams/lb*	*$/lb*	*$/day*	*$/lb*	*percentage*
Cereals & bakery	9.38	0.29	32.05	0.16	0.85	2.91	5.50
Meat	9.85	0.15	66.22	0.33	0.99	6.68	4.95
Eggs	2.47	0.05	54.33	0.27	0.05	1.13	24.04
Dairy	2.41	0.43	5.61	0.03	0.63	1.46	1.92
Fruits & vegetables	18.25	0.40	45.28	0.23	1.18	2.94	7.70
Other food	1.10	2.04	0.54	0.00	0.58	0.29	0.94
Nonalcoholic drinks	35.18	1.48	23.75	0.12	3.11	2.10	5.66
FAFH	0.01	0.60	0.01	0.00	1.22	2.05	0.0035
Alcohol drinks	9.38	0.29	32.05	0.16	0.85	2.91	5.50
					t = $0.002688 Tax per Gram of Sugar[a]		
	grams/day	*lbs/day*	*grams/lb*	*$/lb*	*$/day*	*$/lb*	*percentage*
Cereals & bakery	16.37	0.29	55.94	0.15	0.85	2.91	5.16
Meat	0.22	0.15	1.47	0.00	0.99	6.68	0.06
Eggs	0.36	0.05	7.84	0.02	0.05	1.13	1.86
Dairy	13.80	0.41	33.63	0.09	0.39	0.95	9.47
Fruits & vegetables	12.88	0.43	29.94	0.08	0.63	1.46	5.51
Other food	13.43	0.40	33.31	0.09	1.18	2.94	3.05
Nonalcoholic drinks	36.29	2.04	17.83	0.05	0.58	0.29	16.81
FAFH	35.55	1.48	24.00	0.06	3.11	2.10	3.07
Alcohol drinks	1.38	0.60	2.31	0.01	1.22	2.05	0.30
					t = $0.000165 Tax Per Calorie[a]		
	kcal/day	*lbs/day*	*kcal/lb*	*$/lb*	*$/day*	*$/lb*	*percentage*
Cereals & bakery	351.94	0.29	1202.45	0.20	0.85	2.91	6.81
Meat	162.20	0.15	1090.80	0.18	0.99	6.68	2.69
Eggs	34.24	0.05	753.98	0.12	0.05	1.13	11.01
Dairy	124.36	0.43	289.01	0.05	0.63	1.46	3.27
Fruits & vegetables	362.33	0.40	899.04	0.15	1.18	2.94	5.05
Other food	178.48	2.04	87.68	0.01	0.58	0.29	5.07
Nonalcoholic drinks	801.13	1.48	540.91	0.09	3.11	2.10	4.25
FAFH	122.05	0.60	203.87	0.03	1.22	2.05	1.64
Alcohol drinks	351.94	0.29	1202.45	0.20	0.85	2.91	6.81

Note: Based on one-day dietary recall data from the 2003-04 NHANES (Centers for Disease Control and Prevention, National Center for Health Statistics 2007) and 2002 Personal Consumption Expenditures (U.S. Department of Commerce, Bureau of Economic Analysis 2010).

[a]These tax rates reflect the assumption of exogenous commodity prices and are constructed to achieve approximately the same caloric reduction as the $0.005 tax per gram fat. The tax rates on sugar and calories for the case of endogenous commodity prices differ slightly (i.e. t = $0.002637 tax per gram sugar and t = $0.0001632 tax per calorie). Hence, the ad valorem taxes for each food product for the case of endogenous commodity prices are slightly different as well.

Table A-2a. Sensitivity of Net Social Cost to Doubling of Tax Rates

	Annual Change in Social Welfare (ΔSW) Excluding Changes in Public Heath-Care Costs	Annual Change in Public Health Care Costs	ΔSW Including Change in Public Health Care Costs	Probability that ΔSW Including Public Health Care Costs > 0
	Millions of dollars			
ε_{Lower}				
Fat tax ($t = 0.10$ per gram of fat)	−6,872 (741)	−6,790 (1,426)	−83 (1,059)	0.45
Calorie tax ($t = 0.000326$ per calorie)	−4,623 (457)	−6,791 (1,206)	2,167 (950)	0.99
Sugar tax ($t = 0.005274$ per gram of sugar)	−4,813 (559)	−6,784 (1,502)	1,971 (1,141)	0.96
Uniform food tax ($t = 9.946$ percent)	−5,817 (600)	−6,839 (1,308)	1,022 (1,034)	0.83
ε_{Upper}				
Fat tax ($t = 0.10$ per gram of fat)	−7,308 (823)	−7,040 (1,517)	−267 (1,094)	0.40
Calorie tax ($t = 0.000326$ per calorie)	−4,846 (504)	−7,001 (1,271)	2,156 (975)	0.99
Sugar tax ($t = 0.005274$ per gram of sugar)	−5,021 (615)	−6,955 (1,578)	1,934 (1,164)	0.96
Uniform food tax ($t = 9.946$ percent)	−6,101 (657)	−7,051 (1,370)	950 (1,056)	0.81
$\varepsilon = \infty$				
Fat tax ($t = 0.10$ per gram of fat)	−7,751 (940)	−7,224 (1,608)	−527 (1,125)	0.32
Calorie tax ($t = 0.00033$ per calorie)	−5,039 (561)	−7,132 (1,324)	2,093 (989)	0.99
Sugar tax ($t = 0.005376$ per gram of sugar)	−5,221 (679)	−7,076 (1,643)	1,856 (1,177)	0.95
Uniform food tax ($t = 10.06$ percent)	−6,349 (731)	−7,175 (1,418)	827 (1,068)	0.78

Note: Authors' calculations based on doubling the tax rates in Table A-1. See Table 12a and 12b for more details.

Table A-2b. Sensitivity of Net Social Cost to Halving of Tax Rates

	Annual Change in Social Welfare (ΔSW) Excluding Changes in Public Health Care Costs	Annual Change in Public Health Care Costs	ΔSW Including Change in Public Health Care Costs	Probability that ΔSW Including Public Health Care Costs > 0
	Millions of dollars			
ε_{Lower}				
Fat tax ($t = 0.025$ per gram of fat)	−430 (46)	−1,697 (357)	1,268 (326)	1.00
Calorie tax ($t = 0.0000816$ per calorie)	−289 (29)	−1,698 (302)	1,409 (283)	1.00
Sugar tax ($t = 0.0013185$ per gram of sugar)	−301 (35)	−1,696 (375)	1,395 (350)	1.00
Uniform food tax ($t = 2.4865$ percent)	−365 (38)	−1,713 (328)	1,348 (305)	1.00
ε_{Upper}				
Fat tax ($t = 0.025$ per gram of fat)	−457 (51)	−1,760 (379)	1,303 (344)	1.00
Calorie tax ($t = 0.0000816$ per calorie)	−303 (32)	−1,750 (318)	1,447 (296)	1.00
Sugar tax ($t = 0.0013185$ per gram of sugar)	−314 (38)	−1,739 (394)	1,425 (365)	1.00
Uniform food tax ($t = 2.4865$ percent)	−383 (41)	−1,766 (343)	1,383 (317)	1.00
$\varepsilon = \infty$				
Fat tax ($t = 0.025$ per gram of fat)	−485 (59)	−1,806 (402)	1,321 (361)	1.00
Calorie tax ($t = 0.0000825$ per calorie)	−315 (35)	−1,783 (331)	1,468 (306)	1.00
Sugar tax ($t = 0.001344$ per gram of sugar)	−327 (42)	−1,770 (411)	1,443 (378)	1.00
Uniform food tax ($t = 2.515$ percent)	−398 (46)	−1,797 (355)	1,399 (326)	1.00

Note: Authors' calculations based on halving the tax rates in table A-1. See table 12a and 12b for more details.

Table A-3. Annual Cost per Pound Change in Body Weight for Various Tax Rates

	Excluding Changes in Public Health Care Costs			Including Changes in Public Health Care Costs		
	$t^* = 1/2 \times t$	t	$t^* = 2 \times t$	$t^* = 1/2 \times t$	t	$t^* = 2 \times t$
	Dollars per pound					
ε_{Lower}						
Calorie tax	0.45	0.90	1.81	−2.21	−1.77	−0.85
Sugar tax	0.47	0.93	1.89	−2.19	−1.73	−0.77
Uniform tax	0.57	1.12	2.26	−2.09	−1.54	−0.40
Fat tax	0.67	1.34	2.69	−1.99	−1.31	0.03
ε_{Upper}						
Calorie tax	0.46	0.91	1.84	−2.20	−1.74	−0.82
Sugar tax	0.48	0.94	1.92	−2.18	−1.71	−0.74
Uniform tax	0.58	1.13	2.30	−2.08	−1.53	−0.36
Fat tax	0.69	1.38	2.76	−1.97	−1.28	0.10
$\varepsilon = \infty$						
Calorie tax	0.47	0.86	1.88	−2.19	−1.79	−0.78
Sugar tax	0.49	0.98	1.96	−2.17	−1.37	−0.70
Uniform tax	0.59	1.17	2.35	−2.07	−1.28	−0.31
Fat tax	0.72	1.42	2.85	−1.95	−1.23	0.19

Note: Authors' calculations based on doubling and halving the tax rates in table A-1. Estimates evaluated at the posterior means of data.