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THE MIXED-COMPLEMENTARITY APPROACH TO SPECIFYING AGRICULTURAL SUPPLY IN COMPUTABLE GENERAL EQUILIBRIUM MODELS

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Abstract

In Computable General Equilibrium (CGE) models, it is typically assumed that agricultural resources are smoothly substitutable in neoclassical functions, with flexible prices generating market equilibrium in a setting with full resource employment. Such a specification is often inadequate, especially for analyses of agricultural supply issues. With more disaggregation, the use of smooth, twice-differentiable, production or cost functions to specify agricultural technology is increasingly unrealistic. The purpose of this paper is to show how CGE models formulated as mixed-complementarity (MC) problems can incorporate more realistic, specifications of agricultural supply, drawing on the extensive literature on mathematical programming models applied to agriculture.

We extend a stylized standard neoclassical CGE model to a CGE-MC model that includes Leontief (activity-analysis) technology, endogenous determination of the market regime for agricultural factors (unemployment or full employment), and inequality constraints on agricultural factor use. In an analysis of reduced agricultural water supplies in Egypt, we show how such a model can generate realistic results concerning water use and productivity that cannot be captured in a standard CGE model. The main conclusion is that, in analyses focused on agricultural supply issues, CGE-MC models that selectively incorporate features from the mathematical-programming literature offer a powerful alternative to standard models.

Key Words

Computable General Equilibrium models, Agricultural Mathematical Programming models

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1. INTRODUCTION

In Computable General Equilibrium (CGE) models, it is typically assumed that agricultural resources are smoothly substitutable in neoclassical production or cost functions, with flexible wages, rents, and prices generating market equilibrium in a setting with full resource employment.[1] Although this specification is often adequate, it is also often inadequate, especially when the analysis focuses on resource allocation and production technology issues. With more disaggregation, which is becoming common in CGE models with an agricultural focus, the use of smooth, twice-differentiable, production or cost functions to specify agricultural technology is increasingly unrealistic. The purpose of this paper is to show how CGE models formulated as non-linear mixed-complementarity (MC) problems can incorporate alternative, more realistic, specifications of agricultural technology and supply, drawing on the extensive literature on mathematical programming models applied to agriculture.[2]

First, we present a stylized standard neoclassical CGE model (Section 2). This model is extended to a CGE-MC model (Section 3) that includes Leontief (activity-analysis) technology, endogenous determination of the market regime for agricultural factors (unemployment or full employment), and inequality constraints on agricultural factor use. In an analysis of reduced agricultural water supplies in Egypt (Section 4), we show how such a model can generate realistic results concerning water use and productivity that cannot be captured in a standard CGE model. The main conclusion is that, in analyses focused on agricultural supply issues, CGE-MC models that selectively incorporate features from the mathematical-programming literature offer a powerful alternative to standard models (Section 4). The underlying producer optimization problems for the different problems are presented in an Appendix.

2. THE STANDARD CGE APPROACH TO TECHNOLOGY AND FACTORS

Table 1 presents a stylized neoclassical CGE model. Like most models in the literature, it is formulated as a system of simultaneous equations, all of which are strict equalities. The model is highly simplified — government, foreign trade, and savings-investment are omitted — to focus on producer technology and resources. Producers in each sector maximize profits given their technology, specified by a nested neoclassical value-added function (with factor inputs as arguments) and fixed (Leontief) intermediate input coefficients (equations 1-4). (The underlying

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[1]Early CGE models specified sectoral production functions and derived factor demand functions. Many models now start with cost or profit functions. Chambers (1988) discusses the use of cost functions in agriculture. Computationally, the approaches are essentially identical.

[2]See Agrawal and Heady (1972), and Hazell and Norton (1986).

Table 1: A Stylized CGE Model

#	Equation	Description	# Eq.	Var.
1	$q_s^s = \mathrm{NC}(q_{fs}^f) \quad s \in S$	Sectoral production	S	q_s^s
2	$q_{s's}^{int} = \alpha_{s's}^s q_s^s \quad s' \in S,\ s \in S$	Intermediate input demand	S·S	$q_{s's}^{int}$
3	$p_s^{va} = p_s^s - \sum_{s'} p_{s'}^s \alpha_{s's}^s \quad s \in S$	Value-added price	S	p_s^{va}
4	$w_{fs}^s = \frac{\partial q_s^s}{\partial q_{fs}^f} p_s^{va} \quad f \in F,\ s \in S$	Factor demand	F·S	q_{fs}^f
5	$w_{fs}^s = \bar{w}_{fs}^{dist} w_f \quad f \in F,\ s \in S$	Sectoral factor prices	F·S	w_{fs}^s
6	$q_s^h = NC\left(\sum_s p_s^{va} q_s^s, p_s^s \right) \quad s \in S$	Household demand	S	q_s^h
7	$q_s^s = q_s^h + \sum_{s'} q_{ss'}^{int} \quad s \in S$	Commodity market	S	p_s^s
8	$\bar{q}_f^f = \sum_s q_{fs}^f \quad f \in F$	Factor market	F	w_f
9	$\bar{p} = \prod_s \Omega_s p_s^s$	Cost-of-living index	1	—

Notation

Sets

$s, s' \in S$ sectors (commodities)

$f, f' \in F$ factors

Variables

p_s^s price for sector s

p_s^{va} value-added price for sector s

q_s^h quantity of household demand for output of sector s

q_s^s quantity of output for sector s

q_{fs}^f quantity of demand for factor f from sector s

$q_{s's}^{int}$ quantity of intermediate demand for commodity s' from sector s

w_f wage of factor f

w_{fs}^s wage of factor f in sector s

Parameters

$\alpha_{s's}^s$ quantity of intermediate input s' per unit of output in sector s

Ω_s household expenditure share for sector s

$\bar{p}$ cost of living index

$\bar{q}_f^f$ supply of factor f

$\bar{w}_{fs}^{fdist}$ relative wage distortion for factor f in sector s

Functions

NC neoclassical function

Note: The letters in the column # Eq. refer to the number of elements in the corresponding sets. The domains of some equations (and related variables) are smaller than indicated if each sector does not use all factors or intermediate input commodities. The producer problem is presented in optimization form in the Appendix.

producer optimization problems for this and following models are presented in the Appendix.) The treatment of agriculture is the same as for other sectors. Exogenous relative gaps between sectoral factor rents (wages) are permitted (equation 5). Households receive all factor incomes and spend it on the basis of neoclassical demand functions, derived from utility maximization subject to an income constraint (equation 6). The markets for factors and commodities are in equilibrium (equations 7-8) with flexible wages and prices as equilibrating variables. Production techniques are assumed to be sufficiently flexible to assure that fixed aggregate factor supplies are always fully employed at positive prices. Equation 9 fixes a measure of the aggregate price level, the cost-of-living index, defining the numéraire. Given that the real side of the model is homogeneous of degree zero in prices, the model can only determine relative prices. In Table 1, the number of equations exceeds the number of variables by one — with the exception of the last equation, the last column of Table 1 pairs each equation with a variable of identical dimension. However, given Walras' law, one of the equations is functionally dependent. The model has an equal number of variables and independent equations, and a unique solution can almost invariably be found.

A model with this structure (or variations on the theme; for example, with neoclassical substitutability for intermediate inputs) has proven itself to be a dependable workhorse. It is well-behaved, can be implemented with a small data set, and is almost invariably solvable, generating a solution with strictly positive prices. In some contexts, however, it has serious drawbacks; in particular, if the analysis is focused on agricultural technology and resource questions. Neoclassical production functions exaggerate the smoothness of real-world input substitutability and preclude tests of the attractiveness of discontinuous technical alternatives; for example, introducing new crop varieties. When viewed from a disaggregated perspective, land and water resources are often unemployed, with zero prices.

In many contexts, these shortcomings can be overcome or mitigated if the agricultural supply module of the CGE model incorporates features that are standard fare in agricultural mathematical-programming models, such as Leontief technology and inequality constraints for resources and other production aspects. Path-breaking work in this area is due to Keyzer who developed a tailor-made algorithm for solving general equilibrium models with complementarity relationships used to capture regime shifts in foreign trade and storage policies (Fischer *et al.* 1988; Keyzer *et al.* 1992). Up to this point, such mixed complementarity (MC) CGE models have rarely been used to model the agricultural supply side. Recent advances in computational technology make it possible to solve CGE-MC models at reasonable cost. In the next section, we give a simple example of such a model, with a treatment of agricultural supply that draws on the agricultural mathematical-programming literature.

3. AN AGRICULTURAL CGE-MC MODEL

An MC model consists of a set of simultaneous (linear or nonlinear) equations that are a mix of strict equalities and inequalities, with each inequality linked to a bounded variable in a complementary-slackness condition (Rutherford 1995). Such models are familiar to economists since the Kuhn-Tucker optimality conditions, necessary and sufficient for a global optimum to nearly all well-behaved economic linear and non-linear optimization models (including agricultural-sector mathematical-programming models), define a mixed-complementarity problem. Indeed, all programming models can be written as MC problems. From the perspective of this paper, a CGE-MC model can incorporate features found in agricultural mathematical programming models, with inequalities, that cannot readily be captured in strict-equality simultaneous equation systems. For example, it is easy to incorporate resource unemployment (with associated zero wages), crop rotations, self-sufficiency production targets, stocking targets, and credit rationing.

Table 2 shows a simple CGE-MC model, which is an augmented version of the stylized model in Table 1.[3] Equations with the same number as in Table 1 are unchanged except for slight notational and domain adjustments. New equations are numbered with single or double asterisks. As opposed to the model of Table 1, each sector may generate more than one commodity, with the quantities determined by fixed yield coefficients (equation 1'). This extension is particularly useful when crop-livestock interactions matter. The model distinguishes between sectors (or activities, the set S) and commodities (produced by sectors, the set C). Sector returns per unit activity are given by the sum of commodity prices times yield coefficients (equation 3'). The model also makes a distinction between (agricultural) subfactors (the set FSUB, here land and water) and factors (the set F), one or more of which are aggregates of the subfactors (here one of the factors is a land/water aggregate). Subfactor demand is a Leontief function of the level of the aggregate land/water factor (equation 4'); *i.e.*, land and water are used in fixed proportions in the production of a given crop. For each subfactor, there is an upper limit on the supply share that may be allocated to any single sector (equation 4"). In any applied model, the domain of this equation and associated variables should be constrained to relevant subfactor-sector combinations. The price of the aggregate land/water factor is a linear function of the prices of the subfactors and a penalty variable (equation 5'). The penalty variable (or scarcity price) takes on a positive value when needed to assure that the subfactor constraint is not violated. More specifically, it enters the complementary slackness condition linked to the subfactor constraint (equation 4"): if the constraint is (not) binding, the penalty is positive (zero). The market equilibrium conditions of the subfactors (equation 8') are inequalities linked to the corresponding prices in complementary slackness conditions: if the price is positive, the resource is fully employed; if it is zero, unemployment is permitted. (Cf. note at the bottom of Table 2.) Accounting for one dependent equation, the model has an equal number of variables and independent equations.

Alternatively, Leontief technology may be extended to all factors by substituting equations 1* and 4* for equations 1 and 4. The new profit-maximization condition and the associated complementary slackness condition state that marginal value-added product is less than or equal to the marginal factor cost and that, if the sector activity is positive, marginal value-added product and marginal cost are equal. This condition is written as an inequality to allow the specification of several activities for each "crop" (combination of commodity outputs), some of which may not be operated. If the model is limited to one activity per crop, the range

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[3]The model in Table 2 draws on formulations in Robinson and Gehlhar (1996), and Löfgren *et al.* (1996).

Table 2: A Stylized CGE-MC Model

#	Equation	Description	# Eq.	Var.
1	$q_s^s = \mathrm{NC}(q_{fs}^f) \quad s \in S$	Sectoral production	S	q_s^s
1'	$q_c^c = \sum_s \gamma_{cs} q_s^s \quad c \in C$	Commodity production	C	q_c^c
2	$q_{cs}^{int} = \alpha_{cs}^s q_s^s \quad c \in C,\ s \in S$	Intermediate demand	C·S	q_{cs}^{int}
3	$p_s^{va} = p_s^s - \sum_c p_c^c \alpha_{cs}^s \quad s \in S$	Value-added price	S	p_s^{va}
3'	$p_s^s = \sum_c \gamma_{cs} p_c^c \quad s \in S$	Sector price	S	p_s^s
4	$w_{fs}^s = \frac{\partial q_s^s}{\partial q_{fs}^f} p_s^{va} \quad f \in F,\ s \in S$	Factor demand	F·S	q_{fs}^f
4'	$q_{fs}^{fsub} = \alpha_{fs}^{fsub} q_{f's}^f \quad f \in FSUB;\ s \in S;\ f' = land/water$	Subfactor demand	FSUB·S	q_{fs}^{fsub}
4"	$\psi_{fs}^{\max} \bar{q}_f^{fsub} \geq q_{fs}^{fsub} \quad f \in FSUB,\ s \in S \quad [w_{fs}^{\max} \geq 0]$	Subfactor constraint	FSUB·S	$w_{fs}^{\max}$
5	$w_{fs}^s = \bar{w}_{fs}^{dist} w_f \quad f \in FF,\ s \in S$	Sectoral factor price	FF·S	w_{fs}^s
5'	$w_{f's} = \sum_{f \in FSUB} \alpha_{fs}^{fsub} \left(w_f^{sub} + w_{fs}^{\max} \right) \quad s \in S,\ f' = land/water$	Sectoral subfactor price	S	$w_{lw,s}^s$
6	$q_c^h = NC\left(\sum_s p_s^{va} q_s^s, p_c^c \right) \quad c \in C$	Household demand	C	q_s^h
7	$q_c^c = q_c^h + \sum_s q_{cs}^{int} \quad c \in C$	Commodity market	C	p_c^c
8	$\bar{q}_f^f = \sum_s q_{fs}^f \quad f \in FF$	Factor market	FF	w_f
8'	$\bar{q}_f^{fsub} \geq \sum_s q_{fs}^{fsub} \quad f \in FSUB \quad [w_f^{sub} \geq 0]$	Subfactor market	FSUB	w_f^{sub}
9	$\bar{p} = \prod_s \Omega_s p_s^s$	Cost-of-living index	1	—
1*	$\sum_f w_{fs}^s \alpha_{fs}^f \geq p_s^{va} \quad s \in S \quad [q_s^s \geq 0]$	Leontief first-order condition for profit-max (replacing 1)	S	q_s^s
4*	$q_{fs}^f = \alpha_{fs}^f q_s^s \quad f \in F,\ s \in S$	Leontief factor demand (replacing 4)	F·S	q_{fs}^f

Table 2 cont. on next page

cont. Table 2

New Notation

Sets

$c \in C$	commodities
$f, f' \in FF (\subset F)$	factors without subfactors (all except land/water)
$f \in FSUB$	subfactors (land, water; subfactors to land/water aggregate)
Variables	
p_c^c	price for commodity c
q_c^c	quantity (production level) for commodity c
q_{fs}^{fsub}	quantity of demand for subfactor f in sector s
q_{cs}^{int}	quantity of intermediate demand for commodity c from sector s
w_f^{fsub}	wage of subfactor f
w_{fs}^{max}	penalty on subfactor f in sector s
Parameters	
α_{fs}^{f}	quantity of factor f per activity unit in sector s
α_{fs}^{fsub}	quantity of subfactor f per unit of factor f in sector s
α_{cs}^{s}	quantity of intermediate input c per unit of output in sector s
Ω_c	consumption expenditure share for commodity c
Υ_{cs}	yield of commodity c per activity unit in sector s
ψ_{fa}^{max}	maximum share of the supply of factor f used in sector s
$\bar{q}_f^{fsub}$	supply of subfactor f

Note: Equations with same number as in Table 1 are unchanged except for domain changes. Equations 1* and 4* replace 1 and 4 for a model with Leontief technology also for all factors. Variables entering the associated complementary slackness condition are provided in brackets after the inequalities; for example, the following complementary slackness condition is linked to equation 8' and the lower bound on the subfactor price: $w_f^{sub}\left(\bar{q}_f^{fsub} - \sum_s q_{fs}^{fsub}\right) = 0,\ f \in FSUB$. The two producer problems are presented in optimization form in the Appendix.

of input substitutability would typically be understated. While it is feasible to permit multiple outputs for sectors in a standard CGE model, allowing factor unemployment, constraints on factor use, and the use of Leontief technology, all involving inequality constraints, requires an MC formulation.

4. AN APPLICATION TO EGYPT

In order to demonstrate the significance of the MC approach to CGE modeling, we here briefly present results from experiments using a dynamic (recursive) CGE-MC model of Egypt with a detailed treatment of agriculture.[4] The model is solved for 1990 (the base year), 1993 and 1995, and every five years thereafter until 2020. Apart from being dynamic, this model differs from the stylized model in Table 2 in that it portrays an open economy with a more complete set of domestic institutions (including government and enterprise sectors), as well as investment and savings.

The agricultural supply side of the model quite closely follows the basic model of Table 2 (i.e., the version with activity-analysis technology limited to subfactors). One difference is that the land subfactor is disaggregated by season (summer and winter). Hence, crops may be classified according to whether they use water in summer, winter, or in both seasons (for perennials). Upper limits on subfactor use are only imposed for cotton use of summer land: following Egypt's standard crop rotation, cotton is not permitted to occupy more than one third of the land not covered by perennial crops. An additional equality constraint (with an associated penalty variable) makes sure that the areas for cotton and a short winter clover crop (typically preceding cotton) are equal. Outside agriculture, an MC formulation is used for labor to permit endogenous choice of market regime (unemployment or full employment). The model is solved in GAMS, using PATH or MILES, two solvers for MC problems.[5]

One set of experiments explored the impact of a gradual reduction of agricultural water supplies, reflecting some combination of reduced supplies from the Nile or the transfer of increasing volumes to non-agricultural sectors. In the experiments, agricultural water supplies were reduced in steps of 10%, with declines ranging from 0% to 60% and taking place gradually between 1990 and 2020. On the aggregate level, the impact is quite manageable. As the cut in water supplies changes from 0% to 60%, annual growth in real GDP at factor cost for 1990-2020 falls from 5.2% to 4.8%. However, the impact on the agricultural sector is more severe: its annual growth rate falls from 3.5% to 2.0%. On the micro level, the mix between labor, capital and, for crop activities, a land/water aggregate is driven by profit-maximization subject to a CES function. Given this flexibility, the marginal return to the land/water aggregate is always positive. It is allocated to the land/water subfactors — water, winter land, and summer land — some but not all of which may be slack.

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[4]For additional details, see Löfgren *et al.* (1996).

[5]For GAMS, see Brooke *et al.* (1988). Rutherford (1995) provides more information on PATH and MILES.

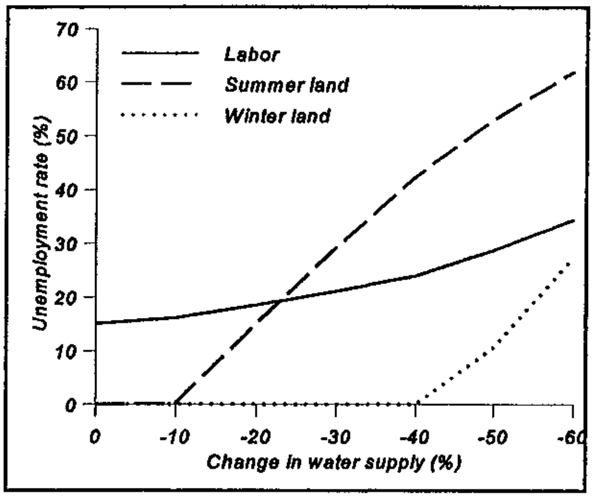

Figure 1: Factor Unemployment Rates with Reduced Water Supplies, Tiger Scenarios

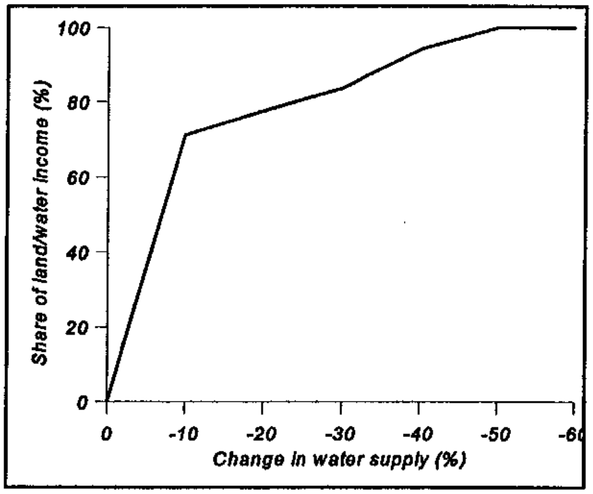

Figure 2: Water Share in Total Land/Water Income, Tiger Scenarios, 2020

Figure 1 shows that, with no cut in water supplies, both land types are fully employed in 2020 while the labor unemployment rate is 15%. When the water supply cut has reached 10%, summer land is taken out of production. Part of the winter land becomes idle when the cut exceeds 40%. For labor, unemployment increases gradually from 15% for no water cut to 34% when the water cut reaches 60%. Accordingly, Figure 2 shows that, as water becomes scarce and excess supplies emerge for both land types, the water share in total land/water income gradually moves from 0% to 100%, i.e., while initially water has excess supply and a zero rent, it eventually becomes binding while both types of land become partly unemployed, with zero rent. In this model, endogenous determination of the factor-market regime (unemployment or full employment) is highly significant. In the background, inequality constraints on the cropping pattern assured that the production structure remained agronomically feasible.

5. CONCLUDING REMARKS

In analyses focused on agricultural supply issues, CGE-MC models that selectively incorporate features from the mathematical-programming literature offer a powerful alternative to standard models. The strength of the CGE-MC approach is that it can capture critical aspects of the institutional and technological structure of agricultural production. Moreover, this is one of the rare occasions when the lunch is free — there is no sacrifice of other features, including the treatment of foreign trade and policy tools, that have made CGE models attractive.

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APPENDIX

In the CGE models in the main body of the paper, the equations relevant to producer behavior are written in the form of first-order conditions. We will here present the underlying producer optimization problems using the same notation as in Tables 1 and 2. In the model of Table 1, the producer in sector s (agricultural or non-agricultural) is represented by equations 1-4. Producer technology is specified as a nested neoclassical value-added function and fixed (Leontief) intermediate input coefficients. In condensed form, the optimization problem for the producers in sector s is to select q^f_{fs} for f ∈ F so as to maximize

$$\pi_s = p^s_s NC(q^f_{fs}) - \sum_{s' \in S} p^{s}\alpha^{s}_{s's} NC(q^f_{fs}) - \sum_f w^s_{fs} q_{fs} \qquad \text{A1}$$

where π_s is profit in sector s. In the process of embedding producer behavior in the full CGE model, new equations defining q^s_s, $q^{int}_{s's}$, and p^{va}_s are added (equations 1-3 in Table 1) while the first-order condition (derivative of A1 with respect to q^f_{fs} set to zero) is rearranged and simplified (equation 4).

In Table 2, two alternative CGE-MC model versions are presented. For the first, behavior and technology for sector s is represented by equations 1, 2, 3, 3', 4, 4', 4'', 5'. The new elements in producer technology are (i) that one of the arguments in the value-added function is a land/water aggregate, made up of land and water in fixed proportions; and (ii) a constraint on sectoral factor use that may reflect agronomic considerations or policy. The condensed version of the underlying profit-maximization problem for s is to select q^f_{fs} for f ∈ F so as to maximize

$$\pi_s = \sum_{c \in C} p^c_c \gamma_{cs} NC(q^f_{fs}) - \sum_{c \in C} p^c_c \alpha^s_{cs} NC(q^f_{fs}) - \sum_{f \in FF} w^s_{fs} q_{fs} - \sum_{f \in FSUB} \sum_{f' = lw} w^{sub}_f \alpha^{fsub}_{fs} q^f_{f's} \qquad \text{A2}$$

subject to

$$\sum_{f' = lw} \alpha^{fsub}_{fs} q^f_{f's} \le \psi^{max}_{fs} \bar{q}^{fsub}_f \qquad f \in FSUB$$

where lw = land/water

In Table 2, the first-order conditions (derivatives of the Lagrangean with respect to q^f_{fs} and w^{max}_{fs}, the constraint function multiplier, both set to zero) are manipulated and simplified to yield equations 4 and 4'', drawing on definitions of q^s_s, q^{int}_{cs}, p^{va}_s, p^s_s, q^{fsub}_{fs}, and w^s_{fs} (the latter for f = land/water aggregate), represented by equations 1, 2, 3, 3'. 4', and 5'.

In the second model version in Table 2, with Leontief technology for all inputs (factors and intermediates), equations 1* and 4* replace 1 and 4. The optimization problem for sector s producers is to select q_s^s so as to maximize

$$\pi_s = \sum_{c \in C} p_c^c \gamma_{cs} q_s^s - \sum_{c \in C} p_c^c \alpha_{cs}^s q_s^s - \sum_{f \in FF} w_{fs}^s \alpha_{fs}^f q_{fs} - \sum_{f \in FSUB} \sum_{f' = lw} w_f^{sub} \alpha_{fs}^{fsub} \alpha_{f's}^f q_s^s$$

subject to equation A2. The full CGE-MC representation of the producer problem is found by adding the same definitions as for the preceding problem, with the exception that an equation is needed for q_{fs}^f (4*) instead of q_s^s. After manipulation, the first-order conditions (derivatives of the Lagrangean with respect to q_s^s and w_{fs}^{max} set to zero) can be restated as 1* and 4".

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