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SPATIAL NETWORKS IN MULTI-REGION COMPUTABLE GENERAL EQUILIBRIUM MODELS

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ABSTRACT

The spatial dimension of economic policy is often important. However, as opposed to partial-equilibrium multi-region programming models, existing multi-region Computable General Equilibrium (CGE) models have rarely explicitly treated geographical space. This paper develops a spatial-network, mixed-complementarity CGE model that combines the strengths of CGE and partial-equilibrium programming models. We implement the model with a prototype data set for a stylized, poor, developing country with rural regions linked to an urban region that provides the gateway to international markets. We demonstrate that the model provides a good framework for analyzing the impact of higher world prices and reduced domestic transportation costs.

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1. INTRODUCTION[1]

Consideration of the spatial impact of economic policy is of critical importance to policy makers. In recent years, the relevance of space has been underlined by a surge in regional strife in nation states throughout the world. The need for spatial disaggregation is underlined by empirical findings which suggest that the regional effects of changes in policies and exogenous shocks may be significantly different from the national average (Nijkamp, *et al.*, 1986, pp. 259 and 261; Miller and Blair, 1985, p. 63). At the same time, models of a single region inside a country for which the national economy is assumed to be given may generate misleading results since they do not allow for inter-regional and nation-region feedbacks. In this environment, spatially disaggregated national models are often the preferred tool for policy analysis.

In recent years, many countries have undergone changes in trade and exchange rate policies. Policy shifts in these areas may have very different effects across regions due to regional differences in economic structure and the existence of high transportation and communications costs. When, as a result, market links across regions are weak, the "national" economy may be better seen as a collection of imperfectly linked regional economies. In this environment, changes in national policy may have little effect on some regions when the changes in prices are too small to induce changes in regional trade. There will also be "threshold effects" whereby changes in, say, trade policy will have little or no effect until the changes are large enough to cause regional producers and consumers to react to changes in prices external to the region — generating sectoral trade flows where before particular regional markets were autarkic.

In the literature on Computable General Equilibrium (CGE) models, a growing number of regionally disaggregated models have emerged in recent years, not only for single countries but also multi-country models. However, these models have rarely explicitly treated geographical space or permitted "regime shifts" for trade flows: if, for the base solution, one region exports to another region, then this trade flow will also be present in all other model

[1]We would like to thank Rebecca Harris and Moataz El-Said for valuable research assistance and Peter Wobst for helpful comments.

simulations. In these respects, they fall short of multi-region models belonging to other traditions, especially those of partial-equilibrium mathematical-programming models that include a spatial network of commodity production, use, and distribution. This paper presents a spatial-network CGE model that combines the strengths of CGE market simulation models and multi-region programming models.

After a brief review of the literature on multi-region models (Section 2), we develop a country-level, spatial-network, CGE model that is formulated as a mixed-complementarity problem (Section 3). We implement the model with a prototype data set reflecting stylized conditions commonly found in poor, developing countries with rural regions linked to an urban region, but with high transportation costs. The urban region provides the gateway to international markets. The prototype data set, including a multi-region Social Accounting Matrix (SAM), is presented in an Appendix. We demonstrate that the model provides a good framework for analyzing the impact of higher world prices and reduced domestic transportation costs (Section 4), in an environment with important threshold effects.

2. BRIEF REVIEW OF MULTI-REGION MODELING[2]

There are many examples of both partial- and general-equilibrium multi-region models. The transportation problem, formulated by Kantorovich in 1939 and Hitchcock in 1941 and solvable with linear programming (LP) algorithms, is the starting point for the partial-equilibrium literature. The classic problem is to minimize the transportation cost that arises when fixed demands in one set of regions (points in space) are satisfied by the transportation of a homogeneous commodity from a second set of regions, each of which has a fixed supply. The model solution generates quantities shipped (by regions of origin and destination) and regional prices. Both price and quantity variables may be zero; i.e., the model endogenously selects the "regimes" for markets (full utilization with a positive

[2] This section draws on Hazell and Norton (l986, pp. 183-186), McCarl and Spreen (1997, pp. 13-15 - 13-17), Thore (1991, pp. 99-101), Nijkamp *et al.* (1986), Hewings and Jensen (1986), and Partridge and Rickman (1997). The review is focused on "bottom-up" multi-regional models.

market-clearing price or excess supply with a zero price) and transportation flows (links may be active, with a positive flow, or inactive, with a zero flow). The solution may be viewed as a market equilibrium, albeit subject to the restrictive assumption of fixed, non-price-responsive, supply and demand quantities.

Enke (1951) and Samuelson (1952) extended the transportation model by introducing price-responsive regional demand and supply functions. Samuelson's formulation shows that the problem of maximizing “net social payoff” (the sum of consumers' and producers' surpluses in the different regions less transportation cost) subject to regional commodity balance equations generates a set of optimality conditions that define equilibrium in each regional market. Much subsequent research was directed toward making Samuelson's model operational and extending it in various directions. Takayama and Judge (1964) generalized Samuelson's approach to multiple products and showed that, if written with linear demand and supply functions, the resulting model could be solved with available quadratic programming (QP) algorithms. Duloy and Norton (1973a, 1973b) linearized the demand side using grid techniques and substituted activity analysis with input substitutability for explicit supply functions; the resulting model could be solved with, at the time, more efficient LP algorithms. Both the QP and LP approaches require that the demand functions be symmetric, a condition that empirically estimated systems are unlikely to satisfy. This shortcoming was overcome with linear-complementarity programming (see for example Takayama and Judge, 1971) and by imposing both price and quantity equilibrium conditions in the primal problem (Plessner and Heady, 1965). Rutherford (1995, pp. 1304-1309) has demonstrated that, with recently developed solvers for non-linear complementarity problems, any neoclassical non-linear demand system can be used.[3]

While these partial-equilibrium models have evolved considerably from the initial transportation model, they have maintained its basic trade treatment: the model endogenously selects the quantities traded, including the regime for each tradable commodity and regional

[3]A non-linear complementarity problem consists of a system of simultaneous (linear or non-linear) equations that are written as inequalities and linked to bounded variables in complementarity slackness conditions. In a mixed-complementarity problem, the equations may be a mixture of inequalities and strict equalities. For details and a mathematical definition, see Rutherford (1995).

link (which may be inactive or may ship in one of the two directions), under the assumption that tradable commodities are homogeneous or perfectly substitutable irrespective of source (from the perspective of the user) or destination (from the perspective of the producer). This assumption, which excludes two-way trade between any pair of regions, is appropriate when commodities are very finely disaggregated. When two-way trade is observed for a commodity at the level of aggregation used in the model, it is preferable to assume imperfect substitutability.

In the economywide modeling tradition, Isard in 1951 published a seminal paper in which he developed the method for the basic multi-region, input-output model (reprinted as Isard [1990]).[4] As opposed to the optimization approach typical of partial-equilibrium models, his model was formulated as a set of simultaneous linear equations. The early multi-region, input-output models suffered from restrictive assumptions similar to those of national input-output models, including fixed production coefficients (excluding input substitutability), and the absence of supply constraints (*i.e.*, reliance on quantity as opposed to price adjustments; Nijkamp *et al.*, p. 263). For Isard's model, the strong assumption of fixed trade coefficients was added to this list.[5] In diametrical opposition to the partial-equilibrium literature, this assumption turns commodities from different sources into perfect complements instead of perfect substitutes. While traded quantities are endogenous (driven by production levels), the inter-regional and international trade regimes (often including cross-hauling) are imposed exogenously by the structure of trade coefficients in the base data set. Nevertheless, subject to these assumptions, the input-output model can also be viewed as solving for a market equilibrium; in this case, a general equilibrium, given the economywide nature of the model.

Much of the subsequent multi-region, input-output literature has been geared toward introducing less restrictive assumptions while maintaining the attractive feature of capturing

[4]In the input-output literature, a distinction is made between “inter-regional” models (based on Isard’s 1951 model) and “multi-regional” models, initially suggested by Chenery (1953) and Moses (1955). In this paper, the term “multi-regional” covers both. The two model classes are compared in Hartwick (1971).

[5]Isard extensively and critically discusses the assumptions of his model, noting that similar assumptions frequently are implicitly contained in more aggregate models (1990, pp. 84-91).

inter-sectoral and regional links throughout the economic system and extending the models to emerging issues such as the environment. Instead of relying on fixed trade coefficients as in Isard's original contribution, these models have relied either on the theory of demand distinguished by place of production (the Armington approach) or on trade pool theory (Nijkamp *et al.*, 1986, pp. 263-265; Batten and Boyce, 1986, p. 389).[6] Hence, in contrast with the partial-equilibrium models, these models do not permit regime shifts in the trade structure. Moreover, while the models include a transportation sector, they have rarely explicitly accounted for spatial aspects.

Like input-output modeling, the more recent CGE literature started out with single-region national models. The earliest and most prolific national multi-region model was done by the Australian ORANI project, which relied on a "top-down" approach (Dixon *et al.*, 1982). Since the mid-1980s, a substantial number of "bottom-up" models have emerged, *i.e.*, models where the primary driving force is derived from the decisions of micro agents. Most single-country models have been applied to the United States and Canada (Partridge and Rickman, 1997); there is also a growing literature on multi-country models in which regions are represented by countries. As opposed to the basic input-output model, CGE models tend to be characterized by price-endogeneity, price-responsive input substitution, and constrained factor supplies. However, available multi-region CGE models are very similar to multi-region input-output models in their treatment of inter-regional trade: space is rarely considered explicitly and most models assume product differentiation using the Armington approach, often complemented by a constant-elasticity of transformation formulation to capture quality differences between output supplied to different destinations.[7]

To conclude, as opposed to most spatial partial-equilibrium programming models,

[6]The Armington approach endogenizes the trade coefficients, making them sensitive to the relative prices of commodities from different origins. Major applications of multi-region, input-output models include Polenske's (1980) model of the United States and the world model in Leontief *et al.* (1977).

[7]This assessment is, *inter alia*, based on a review of the models covered in Partridge and Rickman (1997). The few models that explicitly consider space include Buckley (1992), Wigle (1992), and Elbers (1995). Elbers' paper, which is discussed in footnote 8, is further distinguished by modeling a mix of spatially heterogeneous and homogeneous commodities, with regime shifts in trade for the latter.

economywide multi-region models have typically not incorporated inter-regional trade as a spatial network with regime shifts. In the following section, we turn to the task of specifying such a model.

3. A SPATIAL NETWORK GENERAL EQUILIBRIUM MODEL

In this section, we present a national Spatial Network Computable General Equilibrium model that is formulated as a non-linear, mixed-complementarity problem. In the context of the literature review in Section 2, our model is a generalization of linear, partial-equilibrium, regime-shift models, not only by extending them to general equilibrium but also by including non-linear functions. Our model is characterized by an explicit treatment of space and by permitting regime shifts in regional trade flows. For the sake of simplicity, there is no explicit treatment of savings and investment, and the treatment of the government is very simple. As opposed to the tailor-made solution approaches of Elbers (1995), and Ginsburgh and Waelbroeck (1981), our mixed-complementarity formulation is less restrictive in its assumptions and highly operational since it can be implemented using readily available software.[8]

In our spatial network CGE model, the country is divided into separate domestic regions represented as connected points in space. The regions include households, factors, and commodity-producing activities. Households and producers follow standard utility- and profit-maximizing behavior. Production technology is of the Leontief type (fixed input and output coefficients) which allows activities to shift between positive and zero levels (and also makes it possible to draw on engineering data when defining alternative techniques). Using this specification, it is possible to specify a piecewise linear approximation to a neoclassical

[8]Ginsburgh and Waelbroeck (1981) present an iterative solution procedure using shadow price solutions to formulate income constraints, iterating on welfare weights in the objective function. See also Dixon (1991). Elbers' (1995) solution procedure, successfully applied to a model of Nepal, assumes that there is no substitution between modes of transportation nor are there switches in cost-minimizing paths (chains of links) between regions (1995, pp. 256-258). We use the Path and Miles solvers for GAMS to solve the prototype model of this paper.

production function, which is the approach we use in this paper.[9]

Commodity and factor prices are determined in perfectly competitive regional markets. Commodity trade, between different regions and with the rest of the world, generates demand for transportation services according to a fixed-coefficient formulation. Since the prices of these services are endogenous (like the price of any other commodity), unit transportation costs are endogenous. Commodities are perfect substitutes; *i.e*., they are not differentiated according to region of production or use. The country is a price-taker in international trade. For any commodity and region (which may trade with the rest of the world), import prices exceed export prices. Similarly, price gaps between commodities in different domestic regions reflect the pattern of domestic trade flows and transportation costs (or, more broadly, transaction costs).

Endogenous regime shifts are found in trade, production, and factor markets. In trade, a regime is defined by the set of positive flows between pairs of regions. Any positive trade flow may become inactive or reversed. In the absence of product differentiation, no region will at the same time engage in two-way trade with another region in any given commodity. However, any region may buy from one set of regions and sell to another set. The nation may be engaged in two-way trade with the rest of the world, with one set of domestic regions exporting and another set importing the same commodity. In the production sphere, the model endogenously determines the regional production pattern with the possibility of discontinuing production of commodities produced in the base solution and starting the production of new commodities. In factor markets, two regimes are permitted: full employment with a flexible market-clearing factor price or unemployment with a minimum factor price (zero or higher, depending on institutional conditions).

A mathematical model statement is given in Table 1. In the Table, the row of each

[9]Ginsburgh and Waelbroeck (1981) also allow an "activity analysis" specification of production technology in their modeling approach, although they use neoclassical production functions in their world model. There is no straightforward way to formulate a neoclassical production technology so that production and input demand functions are defined mathematically when an activity is zero, so it is difficult using a neoclassical specification to allow a sector to close down. The Leontief "activity analysis" representation includes zero inputs in its domain and can allow for input substitutability by including several techniques for each activity.

inequality includes a lower bound of zero for the variable that is linked to the inequality in a complementary-slackness relationship. Equations 1-3 define links between domestic regional prices, and between international and regional prices. Equation 1 states that the price of commodity *c* in region *r* plus the unit cost of shipping *c* from region *r* to region *r′* is not less than the price in region *r′*. Equation 1 is linked to the corresponding non-negative shipment variable in a complementary-slackness condition. Hence, if the commodity is shipped from *r* to *r′*, the price link holds as a strict equality. According to Equations 2 and 3, import and export prices define the upper and lower limits for prices in any region *r* (assuming that region *r* can trade directly with the rest of the world). The corresponding complementary-slackness conditions with non-negative import and export variables indicate that, if a commodity is imported (exported), then its import (export) price has to equal the regional price.

Equations 4-7 define production, input use, and demand for transportation services. As noted, the model assumes that all production activities use Leontief technology, specified as a piecewise linear approximations CES functions. Equations 4 and 5 state that, in each region *r*, supplies of outputs and demands for inputs (factors and intermediates) are a linear function of activity levels, disaggregated by technique *t*. Producers maximize profits subject to constant-returns-to-scale production functions. The first-order condition for optimal behavior is given by Equation 6: for each activity *a* in region *r* using technique *t*, marginal cost may not fall below marginal revenue; each positive activity *a* is pursued up to the point where marginal cost and marginal revenue are equal. As shown by Equation 7, demand for any transportation commodity *c* located in region *r* is a linear function of the quantities shipped of commodity *c′* from region of origin *r′* to region of destination *r"*. Note that the transportation commodity is provided by one or more regions that may or may not coincide with the regions of origin or destination.[10]

[10]In this formulation, fixed coefficients are used for transportation demand. Other formulations are possible. The coefficients may, for example, be price-sensitive in a setting with imperfect substitutability between transportation services from multiple regions.

Table 1. Mathematical Statement for Spatial Network CGE model

SETS	
$a \in A$	activities
$c \in C$	commodities (= $C' = C'' \subset I$)
$f \in F$	factors ($\subset I$)
$i \in I$	factors and commodities
$r \in R$	regions ($=R' = R''$)
$t \in T$	techniques

PARAMETERS	
α^{i}_{aitr}	quantity of input i per unit of activity a in region r using technique t
$\alpha^{s}_{crc'r'r''}$	quantity of input c from region r per unit of c' shipped from r' to r'')
α^{x}_{actr}	quantity of output c per unit of activity a in region r using technique t
ψ^{ch}_{cr}	share of commodity c in household demand in region r
ψ^{hg}_{r}	share of government transfers to household in region r
τ^{a}_{ar}	rate of revenue tax for activity a in region r
$\bar{p}^{flo}_{fr}$	minimum price for factor f in region r (≥ 0)
$\bar{p}^{we}_{cr}$	export price for commodity c in region r (in foreign currency)
$\bar{p}^{wm}_{cr}$	import price for commodity c in region r (in foreign currency)
$\bar{q}^{sup}_{fr}$	quantity supplied of factor f in region r
$\bar{r}$	exchange rate (domestic currency per unit of foreign currency)
$\bar{t}^{row}_{r}$	remittance from rest of world to household in region r

VARIABLES	
p^{f}_{fr}	price of factor f in region r
p^{r}_{cr}	price of commodity c in region r
q^{a}_{atr}	quantity (level) of activity a in region r using technique t
q^{e}_{cr}	quantity of commodity c exported to rest of world from region r
q^{h}_{cr}	quantity of commodity c demanded by household in region r
q^{i}_{ir}	quantity demanded of factor or commodity i as input in region r
q^{m}_{cr}	quantity of commodity c imported from rest of world to region r
$q^{s}_{crr'}$	quantity of commodity c shipped from region r to region r'
q^{t}_{cr}	quantity of transportation demand for c produced in r
q^{x}_{cr}	quantity produced of commodity c in r
t^{hg}	value of total transfers from government to households
y_{r}	income of household in region r

EQUATIONS

#	Equation	Domain	Comple-mentarity constraint	Description
1	$p^r_{cr} + \sum_{c''\in C''} \sum_{r''\in R''} p^r_{c''r''} \alpha^s_{c''r''crr'} \geq p^r_{cr'}$	$c\in C$ $r\in R$ $r'\in R'$	$q^s_{crr'} \geq 0$	Link between regional commodity prices
2	$\bar{r}\,\bar{p}^{wm}_{cr} \geq p^r_{cr}$	$c\in C$ $r\in R$	$q^m_{cr} \geq 0$	Upper limit on regional price (= import price)
3	$p^r_{cr} \geq \bar{r}\,\bar{p}^{we}_{cr}$	$c\in C$ $r\in R$	$q^e_{cr} \geq 0$	Lower limit on regional price (= export price)
4	$q^x_{cr} = \sum_{a\in A} \sum_{t\in T} \alpha^x_{actr} q^a_{atr}$	$c\in C$ $r\in R$		Output supply
5	$q^i_{ir} = \sum_{a\in A} \sum_{t\in T} \alpha^i_{aitr} q^a_{atr}$	$i\in I$ $r\in R$		Input demand
6	$\sum_{c\in C} p^r_{cr} \alpha^i_{actr} + \sum_{f\in F} p^f_{fr} \alpha^i_{aftr} \geq \sum_{c\in C} p^r_{cr} \alpha^x_{actr} (1-\tau^a_{ar})$	$a\in A$ $t\in T$ $r\in R$	$q^a_{atr} \geq 0$	First order conditions for profit maximization
7	$q^t_{cr} = \sum_{c'\in C'} \sum_{r'\in R'} \sum_{r''\in R''} \alpha^s_{crc'r'r''} q^s_{c'r'r''}$	$c\in C$ $r\in R$		Transportation demand
8	$y_r = \sum_{f\in F} p^f_{fr} q^i_{fr} + \bar{r}\,\bar{t}^{row}_r + \psi^{hg}_r t^{hg}$	$r\in R$		Household income
9	$q^h_{cr} = \dfrac{\psi^{ch}_{cr} y_r}{p^r_{cr}}$	$c\in C$ $r\in R$		Household consumption
10	$t^{hg} = \sum_{a\in A} \sum_{c\in C} \sum_{t\in T} \sum_{r\in R} \tau^a_{ar} p^r_{cr} \alpha^x_{actr} q^a_{atr}$			Government balance
11	$\sum_{c\in C} \sum_{r\in R} \bar{p}^{we}_{cr} q^e_{cr} + \sum_{r\in R} \bar{t}^{row}_r = \sum_{c\in C} \sum_{r\in R} \bar{p}^{wm}_{cr} q^m_{cr}$			Rest of world current account balance
12	$q^x_{cr} + \sum_{r'\in R'} q^s_{cr'r} + q^m_{cr} = q^i_{cr} + q^h_{cr} + q^t_{cr} + \sum_{r'\in R'} q^s_{crr'} + q^e_{cr}$	$c\in C$ $r\in R$		Commodity market equilibrium
13	$\bar{q}^{sup}_{fr} \geq q^i_{fr}$	$f\in F$ $r\in R$	$p^f_{fr} \geq \bar{p}^{flo}_{fr}$	Factor market equilibrium

Note: The row of each inequality includes a lower limit for the associated complementary-slackness variable.

The next two equations cover household incomes and spending. Equation 8 defines the income of each household in region *r* as the regional factor incomes plus transfers from the rest of the world and the government. According to Equation 9, each household demands commodities according to a Cobb-Douglas utility function, which yields fixed expenditure shares. It is straightforward to use some alternative neoclassical expenditure function (for example, the linear expenditure system).

The last three equations specify system constraints. Equation 10 shows that government revenue consists of producer taxes that are passed on in full to households in the form of transfers. In the current account for transactions with the rest of the world, Equation 11, earnings (from exports and transfers to the households) are strictly equal to expenditures (on imports). The underlying equilibrating variable for this equation is the real exchange rate; i.e., the ratio between (domestic-currency) international (export and import) prices and the domestic price level. For each regional commodity market, Equation 12 imposes equality between quantities supplied (from production, shipments from other domestic regions, and imports from the rest of the world) and demanded (for intermediate input use, household consumption, transportation service input use, shipments to other domestic regions, and exports). Flexible regional prices ensure that this condition holds. Similarly, Equation 13 imposes equilibrium in regional factor markets, linked in complementarity-slackness conditions to factor prices. For these markets two regimes are possible: full employment with a flexible market-clearing price or unemployment with a minimum price (wage) and, implicitly, a market-clearing complementary supply variable.

4. APPLICATION OF THE SPATIAL NETWORK CGE MODEL

4.1. MODEL STRUCTURE AND DATABASE

This section demonstrates the use of the model with regime shifts. Apart from domain restrictions (selectively limiting commodity tradability, regional trade links, and the economic role of selected regions) and limited capital mobility, the applied model is identical to the model presented in Table 1.

Table 2 and Figure 1 show the regional characteristics and the trade links of the applied model. The structure of our stylized model is inspired by an African country such as Mozambique, which has a major (urban) port linking the country with the rest of the world; and rural regions which are linked with the urban region, but not with one another. In this environment, trade between the rural region and the rest of the world has to pass through the urban (port) region. High inter-regional transport costs make it difficult for the rural regions to take advantage of world markets, either as suppliers (exports) or as demanders (imports). The urban region, on the other hand, has more direct access to world markets, and benefits from any trade with the regions, which has to draw on the urban transportation sector.

The model has four regions: two rural, one urban, and a border region. Except for the border region, each region includes one household, up to three factors, and up to five commodity-producing activities. While both rural regions have the full set of factors and activities, the urban region has no agricultural production or (agricultural) land endowment. Households demand all commodities except the non-food crop, and every commodity is used as an intermediate input in one or more sectors. Transportation services are not tradable, either domestically or with the rest of the world. The other commodities are fully tradable. The border region, which may be viewed as geographically adjacent to the urban region, is limited to the unique role of trading with the rest of the world: as opposed to the other regions, it lacks households, production, and factors. The urban region is the pivot in interregional trade, trading with the two rural regions and with the border region, and supplying transportation services required for trading. No direct trade is permitted between the two rural regions or between a rural region and the border region. It is assumed that, in each region, non-agricultural capital is sector-specific whereas, for the rural regions, agricultural land and capital are mobile inside agriculture. Labor is mobile across all sectors but not between regions.

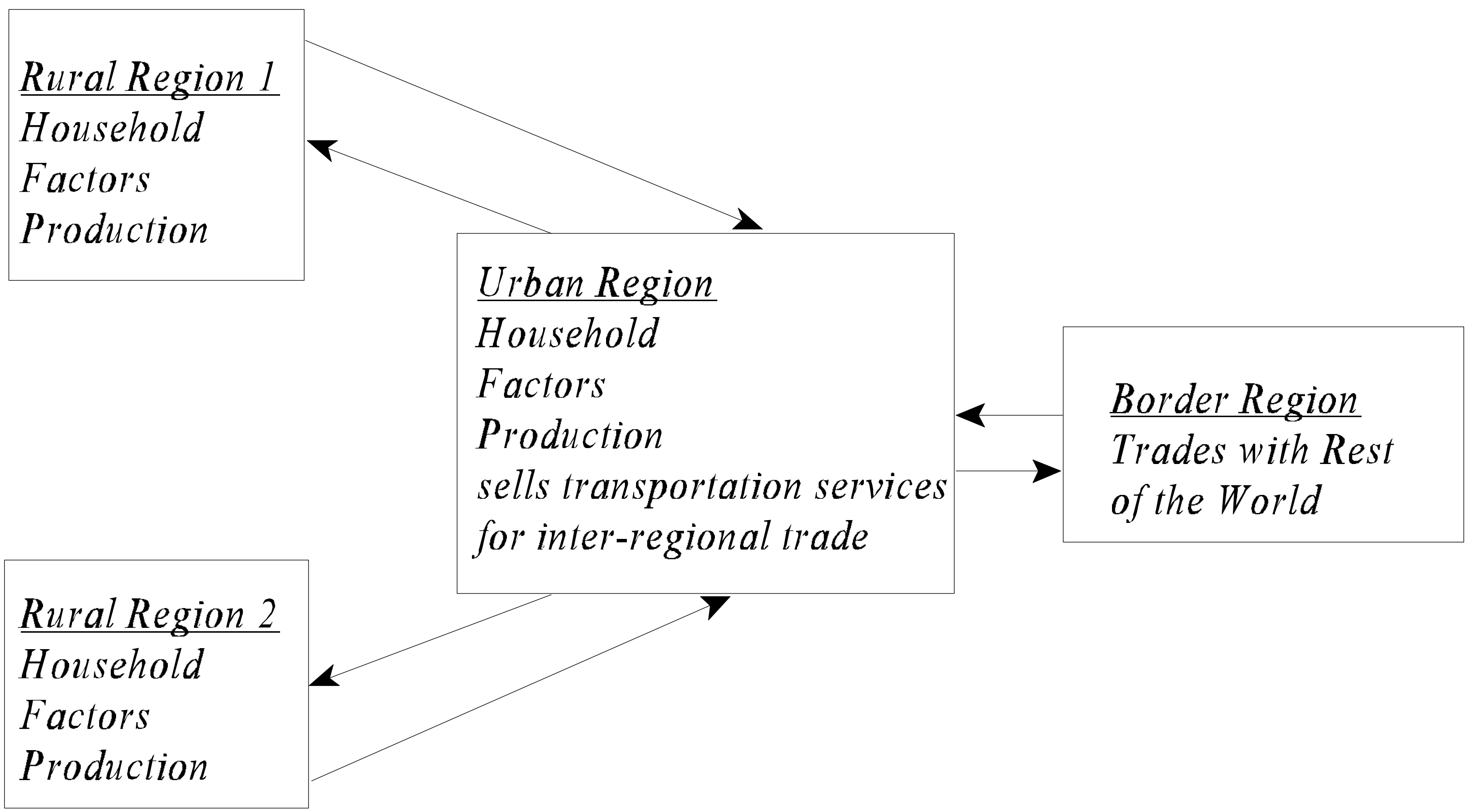
The base solution is calibrated to replicate the SAM that is presented in the Appendix along with supplementary data. According to the SAM, in their trade with the urban region, both *rural regions* buy the other non-agriculture commodity and sell the non-food crop. Among the two remaining crops, rural region 1 exports the subsistence crop and rural region 2 the high-value crop; each rural region is self-sufficient in the other crop. The *urban region* forwards part of its rural purchases of the non-food crop to the border region while supplementing its purchases of the high-value and subsistence crops with imports coming from the border region. In addition, the urban region covers parts of its rural sales of the other non-agriculture commodity with imports from the border. The *border region*, which is the only link to the rest of the world, exports the non-food crop and imports the other three tradables.

In production, the main difference between the two rural regions is that the subsistence crop is the main crop in region 1 while the high-value crop dominates in region 2. In both regions, non-agriculture accounts for 40% of GDP at factor cost. In the urban region, other non-agriculture accounts for almost 60% of GDP with the rest claimed by transportation services. The regions also differ in other respects, including production techniques and consumption patterns. For each production activity, capital-labor substitution is specified along a linearized CES isoquant.

Table 2. Applied Spatial Network CGE Model: Regional disaggregation and trade links

	Rural 1	Rural 2	Urban	Border
Households	One	One	One	None
Factors	Labor Capital Land	Labor Capital Land	Labor Capital	None
Activities/ Commodities	Subsistence agriculture, High-value agriculture, Non-food crop, Transportation, Other non-agriculture	Subsistence agriculture, High-value agriculture, Non-food crop, Transportation, Other non-agriculture	Transportation, Other non-agriculture	None
Supplier of transport services for inter-region trade	No	No	Yes	No
Trading partners	Urban	Urban	Rural 1 Rural 2 Border	Urban Rest of World

Figure 1. Spatial network in applied model. (Note: Arrows indicate possible domestic trade flows for tradables.)



4.2. SIMULATIONS

We use the model to simulate the impact of increased world prices for the high-value crop and of reduced inter-regional transportation costs. In our first set of experiments, we increase world prices of high-value agriculture in 20% increments, with the world price of high-value agriculture ending up three times the base value after ten experiments. Figures 2-6 summarize the results. The initial position is that the national imports of the high-value crop correspond to around 18% of domestic output. Production and consumption changes in response to a 20% increase in the world price of the high-value crop bring about self-sufficiency with very small positive changes in value-added for rural regions and a similarly small decline in urban value-added (Figures 2 and 5). Crop exports are affected for both rural regions, i.e., not only for region 2 which sells the high-value crop (Figures 3-4).

Price increases between 20% and 60-80% — a range within which the nation remains self-sufficient — have no impact (cf. Figure 5). Starting from the point when the nation shifts toward exporting the crop, increases in the world price raise value-added in all regions, especially in the urban region (which benefits from the boost in demand for transport services that results from increased domestic and international trade) and more in rural region 2 (which exports the high-value crop) than in rural region 1 (Figure 2). Multiple changes take place in the trading regimes of both rural regions until the price increase has reached 120%, at which point also region 1 exports the high-value crop (Figures 3-4). In international trade, the increase in high-value exports is accompanied by growth in imports of the subsistence crop and the other non-agriculture commodity, and a shift from exports to self-sufficiency in the non-food crop (Figure 5). In rural-urban trade, large changes in urban purchases of the high-value and other non-food crops are linked to the urban region's role as conduit for international trade. In its trade with the rural regions in the subsistence crop, the urban region shifts from buyer to seller as the nation boosts its imports of this crop (Figure 6).

Figure 2. Experiments with increased world price for high-value crop: Value-added by region

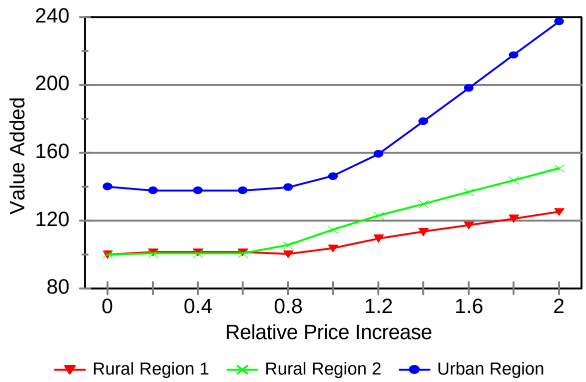


Figure 3. Experiments with increased world price for high-value crop: Net exports from rural region 1

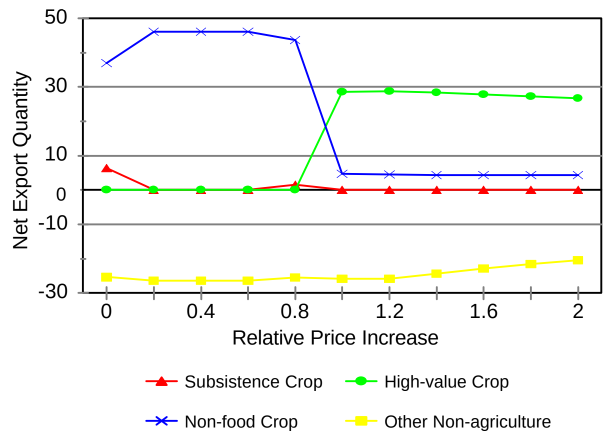


Figure 4. Experiments with increased world price for high-value crop: Net exports from rural region 2

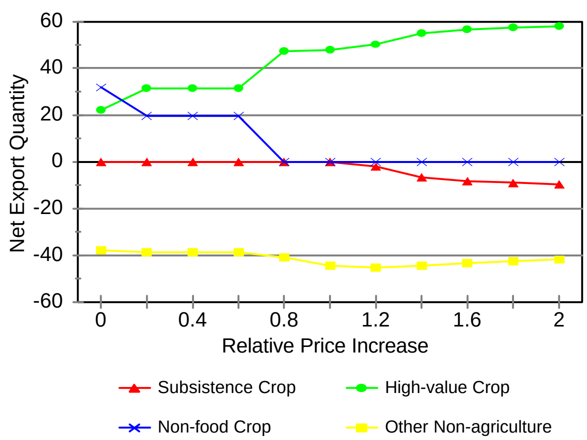


Figure 5. Experiments with increased world price for high-value crop: Net exports from urban region to ROW

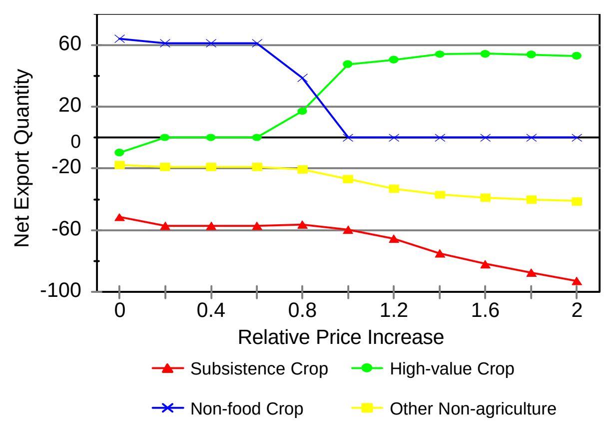
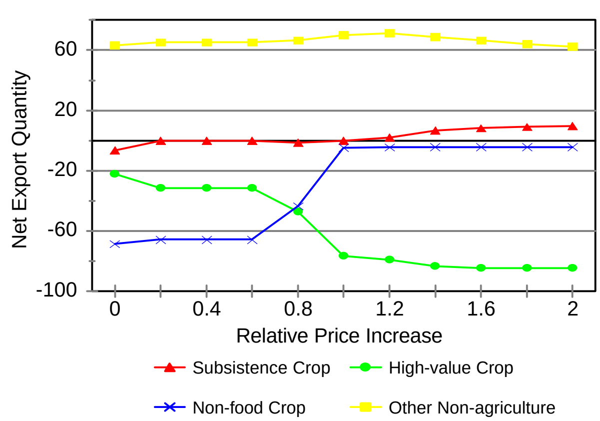


Figure 6. Experiments with increased world price for high-value crop: Net exports from urban region to rural regions



Increases in the high-value crop price beyond 120% lead to relatively small changes, primarily due to a bottleneck in the urban transportation sector.

In a second set of experiments, we lower, in decrements of 7.5%, the coefficients for transportation service demand per unit shipped between urban and rural regions, reaching a cut by 75% after ten experiments. Transportation demand per unit shipped between the urban region and the border (port) region do not change — the experiments focus only on rural-urban trade, consolidating the domestic market.

Figures 7-11 summarize the results. In this case, rural value added increases steadily, with a stronger increase for region 1 which has higher transportation costs; the urban region suffers due to a decline in the returns earned by its transportation sector (Figure 7). In response to the cut in transportation costs, rural region 1 shifts toward exports of the non-food crop while reducing its net exports of the two other crops (Figure 8). Rural region 2 follows a similar but weaker trend except for the fact that it remains self-sufficient in the subsistence crop throughout the simulations (Figure 9). For both rural regions, the reduction in transportation costs boosts their demand for imports of the other non-agriculture commodity. On the national level, these changes are associated with increased exports of the non-food crop, and slightly increased imports of all other tradables (Figure 10). The pattern of shifts in rural-urban trade is implied by the preceding discussion: most importantly, the urban region increases its purchases of the non-food crop while selling more of the non-agriculture commodity (Figure 11). Aggregation of the trade figures indicate that, as expected, increased productivity or investments in the transportation sector — the partial removal of a "natural" trade barrier — boosts both domestic and foreign trade.

In addition, we conducted a third set of simulations where we repeated the increases in the world price of the high-value crop of the first set of experiments in a setting with a lower unit transportation demand for domestic trade: the unit transportation coefficient was lowered to 75% of the base value throughout this set of simulations. Compared to the base, all regions gained more in value-added than for the first experiments where world prices increased in isolation. Hence, in a setting with growing

Figure 7. Experiments with reduced domestic transportation unit costs: Value-added by region

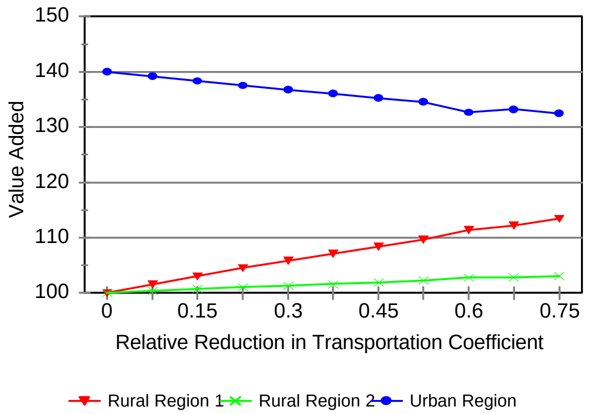


Figure 8. Experiments with reduced domestic transportation unit costs: Net exports from rural

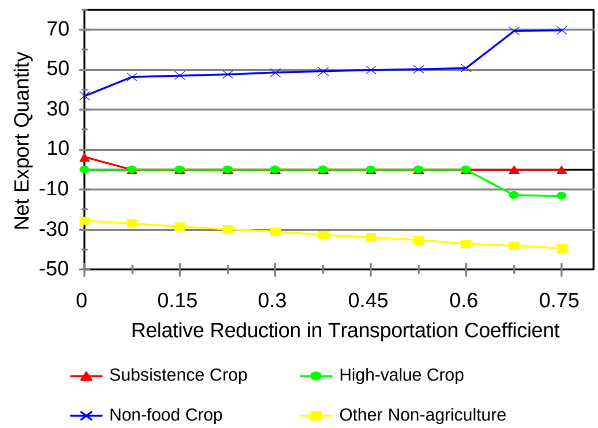


Figure 9. Experiments with reduced domestic transportation unit costs: Net exports from rural region

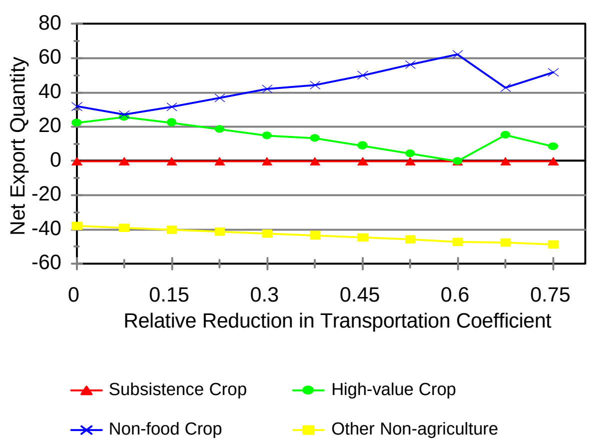


Figure 10. Experiments with reduced domestic transportation unit costs: Net exports from urban region to ROW

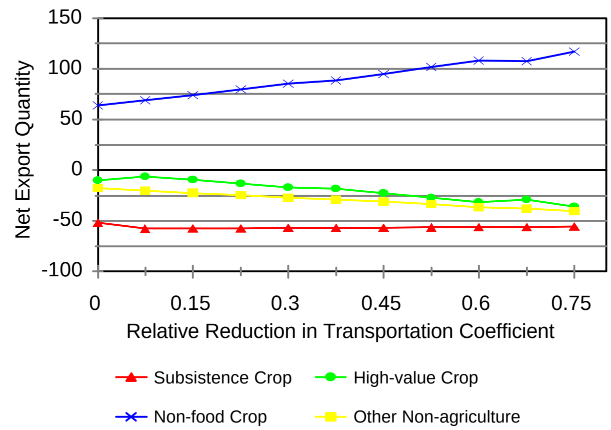
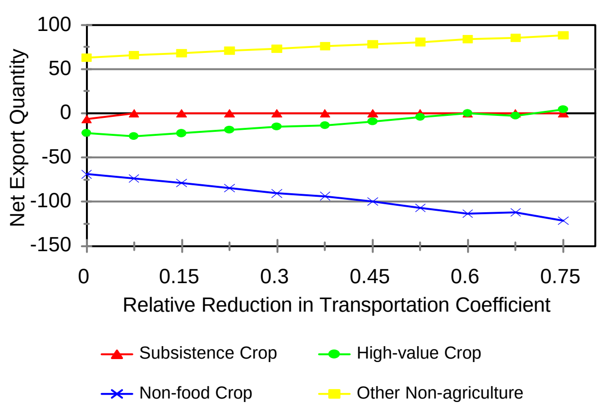


Figure 11. Experiments with reduced domestic transportation unit costs: Net exports from urban region to rural regions



demand for transportation services, a productivity increase for this sector can generate a win-win outcome.

In sum, the results demonstrate the ability of the model to capture threshold effects and a diverse pattern of regional impacts. In terms of trade policy, the results illustrate the potential pitfalls of assuming a continuous response. In the transportation area, the results suggest that increased productivity of transportation services, while having a positive aggregate impact, may hurt the region that provides transportation services. However, if increased productivity in this sector is introduced in the context of growing trade, all regions may end up as winners. This result points to potentially important complementarities between improved penetration of export markets and investments in domestic transportation networks.

5. CONCLUSION

We have demonstrated that a mixed-complementarity CGE model can incorporate a multi-region spatial network with region-specific transportation costs that permit regime shifts and threshold effects in regional trade and production. Our application of the model suggests that it provides a good framework for analyzing issues such as the impact of higher world prices and reduced domestic transportation costs. The framework should also be useful for many other kinds of policy analysis. The distinguishing features of the model play an important role in the simulations: multiple regime shifts occur in domestic and foreign trade; responses are in many instances discontinuous; and disaggregated regional impacts are diverse.

The results are compatible with findings in the literature on multi-region CGE models according to which spatial disaggregation matters in many contexts. Explicit inclusion of transportation costs is likely to be important when transportation costs constitute a significant share of prices, typically in settings where the transportation infrastructure is underdeveloped and/or when population density is low and the population is dispersed. Regime shifts in trade are more likely when large price changes occur for relatively homogeneous commodities. In terms of policy analysis, the results indicate the importance of considering infrastructure investment as a crucial part of a development strategy involving trade liberalization and an increased role for foreign trade.

The choice of model structure is inextricably linked to data availability and the purpose of the analysis. Rather than the purposefully pure model presented in this paper, hybrid models are more likely to be useful in applied work. Such models would incorporate the spatial-network, regime-shift formulation for the parts of the model that are most disaggregated (for example, grain commodities in a model focused on grain-market policies) while, in other areas, they might draw on features typical of existing multi-region CGE models (most importantly product differentiation, but perhaps also a less data-demanding treatment of transportation costs).

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APPENDIX

The bulk of the model data are derived from the SAM in Table A.1. Like the model, it is regionalized: the accounts for factors, households, activities and commodities are disaggregated by region. The government account is associated with a “national” region. The commodity accounts of importing regions pay the exporting region both for the imported commodity and for the urban transportation commodity for transportation services. For the sake of compactness, the border region has been merged with the rest of the world; as a result it does not have disaggregated commodity accounts. When one account purchases commodities from more than one source (for some domestic trade) or purchases more than one commodity (for the border/rest of the world region), the SAM does not reveal the disaggregation of payments for transportation services. It was assumed that these payments were split according to shares in traded commodity value shares (excluding transportation cost).

In addition, the SAM is complemented by additional data regarding activity techniques, and gaps between import-export prices in international trade. For the activities, a substitution elasticity of 0.5 was used when defining alternative techniques that together approximate capital-labor substitution along a CES isoquant. In the base (reflected in the SAM), all tradables are traded internationally. For the active trade direction (import or export), the price is normalized to unity. If a commodity is imported in the base, the assumed export price is 0.75; if a commodity is exported, the import price is set at 1.25. The transportation coefficients are calibrated on the basis of the SAM. However, information in the SAM has to be supplemented for inactive trade links and when a column (a commodity account or the border/RoW) purchases commodities from more than one row. As a result of assumptions made, the transportation coefficients for rural region 1 are approximately twice as high as for region 2 for all agricultural crops but identical for the non-agricultural commodity.

Table A.1. Social Accounting Matrix for Spatial Network CGE Model

	R1.LAB	R1.CAP	R1.LND	R1.HHD	R1.SUBS-A
R1 .LAB					15.00
R1 .CAP					5.00
R1 .LND					10.00
R1 .HHD	55.00	25.00	20.00		
R1 .SUBS-C				29.61	3.00
R1 .HIVA-C				12.17	
R1 .TRN-C				6.00	1.50
R1 .ONAG-C				59.22	5.00
TOTAL	55.00	25.00	20.00	107.00	39.50

	R1.HIVA-A	R1.NFCR-A	R1.TRN-A	R1.ONAG-A	R1.SUBS-C
R1 .LAB	5.00	10.00	5.00	20.00	
R1 .CAP	1.67	3.33	5.00	10.00	
R1 .LND	3.33	6.67			
R1 .SUBS-A					39.50
R1 .SUBS-C				1.50	
R1 .HIVA-C	1.00			1.50	
R1 .NFCR-C		2.00		1.50	
R1 .TRN-C	1.00	2.00	1.00	3.00	
R1 .ONAG-C	1.67	3.33	2.50	7.50	
NAT.GOV	1.00	1.00	1.00		
TOTAL	14.67	28.33	14.50	45.00	39.50

	R1.HIVA-C	R1.NFCR-C	R1.TRN-C	R1.ONAG-C	R2.LAB
R1 .HIVA-A	14.67				
R1 .NFCR-A		28.33			
R1 .TRN-A			14.50		
R1 .ONAG-A				45.00	
R2 .HHD					40.00
U .TRN-C				5.13	
U .ONAG-C				29.09	
TOTAL	14.67	28.33	14.50	79.22	40.00

Note: Row totals (not in Table) are equal to column totals. In each segment, rows with no values (all zeros) have been suppressed. Abbreviations are explained at the end of the Table.

cont. Table A.1

	R2.CAP	R2.LND	R2.HHD	R2.SUBS-A	R2.HIVA-A
R2 .LAB				3.34	10.00
R2 .CAP				3.33	10.00
R2 .LND				3.33	10.00
R2 .HHD	40.00	20.00			
R2 .SUBS-C			10.67	1.00	
R2 .HIVA-C			15.39		3.00
R2 .TRN-C			4.00	0.50	3.00
R2 .ONAG-C			76.94	1.67	5.00
NAT.GOV					1.00
TOTAL	40.00	20.00	107.00	13.17	42.00

	R2.NFCR-A	R2.TRN-A	R2.ONAG-A	R2.SUBS-C	R2.HIVA-C
R2 .LAB	6.66	5.00	15.00		
R2 .CAP	6.67	5.00	15.00		
R2 .LND	6.67				
R2 .SUBS-A				13.17	
R2 .HIVA-A					42.00
R2 .SUBS-C			1.50		
R2 .HIVA-C			1.50		
R2 .NFCR-C	2.00		1.50		
R2 .TRN-C	2.00	1.00	3.00		
R2 .ONAG-C	3.33	2.50	7.50		
NAT.GOV	1.00		1.00		
TOTAL	28.33	13.50	46.00	13.17	42.00

	R2.NFCR-C	R2.TRN-C	R2.ONAG-C	U.LAB	U.CAP
R2 .NFCR-A	28.33				
R2 .TRN-A		13.50			
R2 .ONAG-A			46.00		
U .HHD				60.00	80.00
U .TRN-C			7.64		
U .ONAG-C			43.30		
TOTAL	28.33	13.50	96.94	60.00	80.00

cont. Table A.1

	U.HHD	U.TRN-A	U.ONAG-A	U.SUBS-C	U.HIVA-C
R1 .SUBS-C				5.39	
R2 .HIVA-C					22.11
U .LAB		25.00	35.00		
U .CAP		35.00	45.00		
U .SUBS-C	59.24		4.00		
U .HIVA-C	27.57		4.00		
U .NFCR-C			4.00		
U .TRN-C	7.43		8.00	6.41	4.46
U .ONAG-C	52.76		20.00		
BRD.ROW				51.44	5.00
TOTAL	147.00	60.00	120.00	63.24	31.57

	U.NFCR-C	U.TRN-C	U.ONAG-C	NAT.GOV	BRD.ROW
R1 .HHD				2.00	5.00
R1 .NFCR-C	24.83				
R2 .HHD				2.00	5.00
R2 .NFCR-C	24.83				
U .HHD				2.00	5.00
U .TRN-A		60.00			
U .ONAG-A			120.00		
U .NFCR-C					54.42
U .TRN-C	8.76		2.55		9.62
BRD.ROW			22.60		
TOTAL	58.42	60.00	145.15	6.00	79.04

Abbreviations

R1	= rural region 1	SUBS-A	= agricultural subsistence activity
R2	= rural region 2	HIVA-A	= agricultural high-value-added activity
U	= urban region	NFCR-A	= agricultural non-food-crop activity
BRD	= border region	TRN-A	= transportation activity
NAT	= nation	ONAG-A	= other non-agricultural activity
LAB	= labor	SUBS-C	= agricultural subsistence activity
CAP	= capital	HIVA-C	= agricultural high-value-added commodity
LND	= (agricultural) land	NFCR-C	= agricultural non-food-crop commodity
HHD	= household	TRN-C	= transportation commodity
GOV	= government	ONAG-C	= other non-agricultural commodity
ROW	= rest of world		

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