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ALTERNATIVES FOR MANAGING DROUGHT: A COMPARATIVE COST ANALYSIS

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California Agricultural Experiment Station
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Proposed running head: Alternatives for Managing Drought

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ABSTRACT

The question addressed by this study is how a large urban water district can best respond to a drought. Using a computer model of a representative district, we find that a combination of conjunctive use and water marketing is well over an order of magnitude cheaper than the traditional alternative of construction of new storage capacity. The indicated cost saving can be explained by the intermittent nature of the transfer, corresponding to the intermittent demand. Comparing costs to benefits, the consumer-surplus loss otherwise entailed by raising prices to cut back on consumption in the event of a drought, we find that construction of new storage does not pass a benefit/cost test, but introduction of conjunctive use/water marketing does.

ALTERNATIVES FOR MANAGING DROUGHT: A COMPARATIVE COST ANALYSIS

I. INTRODUCTION

The problem addressed by this study is how to determine the least-cost combination of alternatives to meet periodic water shortages. A solution to this problem may involve demand management strategies and/or supply augmentation. Supply augmentation approaches may be purely structural (such as developing new local storage capacity) or a mix of structural and nonstructural (such as "conjunctive use" of surface and groundwater supplies combined with water exchanges or sales). The application is to the East Bay Municipal Utility District (EBMUD), which includes large portions of Alameda and Contra Costa counties on the east side of the San Francisco Bay, but the concepts and methods (and some of the findings) will be relevant to other districts.

Other analyses of drought-contingent water transfers investigate the benefits of interruptible irrigation in low-flow years to maintain hydropower supply reliability ([10], [12]). Michelson and Young [13] examine interruptible irrigation "water-supply option contracts" to satisfy municipal water demands during drought. Our approach is similar but expands on the options considered. Thus, while they assume that the need for additional drought water supply is determined a priori, we consider the effective welfare costs of demand-reduction strategies as well as the costs of supply augmentation in the form of expansion of surface storage or of effectively storing water underground. They focus on purchase of water-rights and drought option contracts which are comparable to still another option that we consider—intermittent water marketing. Our results can easily be converted into Michelson and Young's "present value of the benefit of an option contract" by recouping the present-value cost of each of our options and subtracting the present-value cost of the water-marketing option (their option exercise cost).

In order to compare the costs of the various combinations of options, a computer program has been developed to model operation of the EBMUD system under a wide variety of environmental and management scenarios. Separate cost estimates for construction and operation of the supply-side options are calculated with engineering data from EBMUD and other sources. The next section describes the computer model. In section III, supply-side cost estimation procedures are described and cost estimates are presented, in terms of dollars per af of water provided in drought years, for key reservoir options under consideration. The same approach to a range of conjunctive-use/water-marketing options is applied in section IV. Finally, in section V the cost estimates are compared to the benefit of averting or mitigating a shortfall, the loss in surplus that would be entailed by restricting consumption through higher prices.

II. THE EBMUD SYSTEM AND OPERATIONS MODEL

A. The EBMUD System

The main features of the EBMUD system are two large reservoirs on the upper Mokelumne River (approximately 80 miles to the northeast of the service district), three aqueducts to bring water to the district, five local or terminal reservoirs, and six local treatment plants. Of the two reservoirs on the River, just Pardee, the upper, smaller of the two, with a capacity of 211 thousand acre-feet (kaf), is currently connected to the aqueducts. The larger (430 kaf) Camanche Reservoir is used for supplying senior water rights (mainly agricultural users in the reservoir area), stream flow regulation, and flood control. Terminal storage capacity is about 150 kaf. These reservoirs serve a district of about 350 thousand households or 1.1 million people.

Before the current drought, annual consumption had reached a maximum of about 240 kaf, which is equivalent to an average over the year of 220 million gallons per day (mgd). EBMUD is entitled to a substantially larger amount of Mokelumne water, about 360 kaf or 325 mgd.

The issue that motivates this study is whether the district needs an addition to terminal storage, both to help it get through periods of shortage and to protect against sudden outage due to disruption of the aqueducts at their most vulnerable point, where they traverse the Delta, by a natural disaster such as an earthquake or flood. EBMUD began an in-house planning process to address this issue in early 1987 and solicited public input over the next couple of years. Findings and recommendations are given in a Final EIR (EBMUD [7]). The main recommendation is for construction of a large, new local reservoir, preferably in Buckhorn Canyon, just to the east of the existing Upper San Leandro Reservoir. The proposed Buckhorn Reservoir would have a capacity of 145 kaf, making it almost as large as all of the existing local reservoirs combined. A variant of this plan would involve cooperation with the adjacent Contra Costa Water District (CCWD) in construction of a new reservoir, Los Vaqueros, to serve both districts. As it appears CCWD intends to go ahead with Los Vaqueros in any event, the issue for EBMUD is whether to join in an expanded effort.

EBMUD argues that a new reservoir, preferably a 145 kaf Buckhorn, would best meet the objectives of averting both drought-related shortfalls and sudden disruptions. However, EBMUD's own engineering data reveal that separate solutions for each threat, namely, construction of an earthquake-secure aqueduct and a smaller 55 kaf Buckhorn reservoir (which is the amount of storage EBMUD analysis requires for the drought problem alone), result in lower costs, as we show in the more detailed report on which this paper is based (Fisher *et al.* [8]). Moreover, as we show in this paper, once the earthquake-security and drought problems are decoupled, drought-relief options other than terminal storage can be considered which have orders of magnitude lower unit costs.

B. Structure of the Model

The computer program is a mass balance model, allocating water flowing down the Mokelumne River to downstream releases, storage, transport, or consumptive use. In each run of the model, a static (constant average use) EBMUD system is subjected to a sequence of variable runoff patterns. Shortage patterns (frequency and severity) can then be estimated for each planning scenario. The model is highly parameterized, allowing examination of a wide variety of physical and operational scenarios.

A flow file contains assumed inflows to Pardee Reservoir by month, based on U.S. Geological Survey records from October, 1927, through September, 1989. Clearly, past flow patterns will not recur in the future. However, use of the historical patterns provides a reasonable starting point for estimating the frequency of shortages under various assumptions. Synthetically generated flow patterns could also be used. For example, if the changes in precipitation patterns resulting from global warming can be estimated, synthetic flows could be generated to indicate how a given system would perform under the new conditions.

Key physical parameters include seepage losses in the river and evaporation from the reservoirs. The important structural parameters are size of existing storage reservoirs (for example, how much of the bottom storage in existing reservoirs could be extracted during a shortage), integration of new storage reservoirs (such as Buckhorn and Los Vaqueros), and capacity of conveyance facilities. Operational parameters include maximum acceptable demand reductions in drought (25 percent to 39 percent in EBMUD planning), storage levels, releases for downstream water-rights holders and for environmental purposes, and water-transfer/conjunctive-use programs.

With respect to storage levels, a critical parameter is the October carryover target (i.e., the amount of total storage to be carried into the next water year). Current EBMUD practice, adopted in this study, appears to call for a target carryover of about 1.2 times annual demand or use. It is important to recognize that this is not a particularly "economic" approach in that no attempt is made to optimize reservoir operation with respect to water inventory; we rely on the existing "rules of thumb" of carryover targets and allowable supply reductions to address the trade-off between supplying current period needs and providing drought security for future periods. A recent survey on planning procedures for drought at local water agencies finds that most agencies "plan for enough water for normal times and for a reserve to guard against drought and other problems..." ([9]) with no explicit or implicit consideration of balancing current and future benefits of releasing the last unit of water. In the water-resource literature, models have been developed that account for the stochastic nature of hydrological inflows. However, stated objectives are almost uniformly based on proximity and variation from some specified target storage volume (Loucks, Stedinger, and Haith [11]).

With respect to water transfers, one option to increase water supplies during drought is to reduce releases from Camanche Reservoir for downstream water-rights holders, in turn allowing EBMUD to keep more water in Pardee Reservoir for transmission through the aqueducts. This could be done by purchase or as part of a conjunctive-use program in which reduced surface water deliveries are compensated by pumping extra groundwater. Both options will be considered here.

A working file takes information from the flow and parameter files and operates the system on a month-by-month basis: distributing and releasing water, calling for demand reductions in time of drought, and so on. The output from this file is a detailed record of hypothetical operations over the period chosen. Each month begins with a set of initial values for the system. Inflows are drawn from the flows file while demand is drawn from the parameter file. Demand will be reduced if drought reductions are in effect. Aqueduct flows from Pardee are drawn so that demand and target terminal-storage levels are met if possible. Next, releases from Camanche for downstream commitments, flood control, or other purposes (e.g., spillage) are computed. Finally, Pardee releases are computed. Now, new Camanche and Pardee storage levels can be computed.

The month of April is treated separately in the model. This is when basic decisions are made about how the system will be operated over the next year. April is chosen because, by April 1, most of the winter's precipitation has already fallen and the snowpack has been assessed. Thus, the runoff for that water year is known with a fair degree of certainty. In April, predictions are made about the storage levels in EBMUD reservoirs which will exist on October 1. If storage levels will be adequate, then the system operates normally. If October 1 storage falls below acceptable carryover minimums, then a drought response will be necessary. The model requires conservation as needed to ensure that the October 1 carryover level is met—until the maximum acceptable conservation level is reached. Thereafter, storage is allowed to fall below acceptable carryover minimums.

III. COST ESTIMATION OF RESERVOIR OPTIONS

To determine the effective unit cost of water supplied by the proposed projects, we use three variants: (1) unit cost calculated over the defined planning horizon, (2) unit cost calculated over the approximated lifetime of reservoir projects, and (3) unit cost of a perpetuity (a project that provides benefits "forever"). The concept most often employed in the comparison of different possible capital expenditures is that of economic equivalent unit cost over a defined planning horizon. This is the standard method employed by the California Department of Water Resources (DWR); see, for example, DWR [5]. EBMUD has defined its planning horizon to be 30 years. However, reservoir projects under consideration have expected lifetimes of between 50 and 100 years. Since EBMUD presents some data for an 80-year operation period, this time span will be used as an approximation of the lifetime of various projects.

The economic equivalent unit cost of a project is the ratio of the equivalent annual cost to the annual "water-supply accomplishments." To calculate the equivalent annual cost, the sum of the present value of the costs for each year, or equivalently the total present-value cost, of the project is multiplied by the capital recovery factor (see Riggs and West [16]; details of our computational formula available on request). Since the objective of the project is to create a standby water supply capable of alleviating hardships during drought, rather than a yearly or even daily online supply, the water-supply accomplishments are defined to be the water actually delivered in drought years that otherwise would be unavailable. Thus, the water-supply accomplishments of each project are evaluated using the 62-year hydrological record for the Mokelumne River watershed, and a yearly average is calculated to obtain the annual water-supply accomplishments.

In the present analysis of reservoir options, we restrict our attention to Buckhorn and Los Vaqueros, the principal proposals in EBMUD's Final EIR [7]. The water-supply accomplishments of additional storage are calculated using the model described in the preceding section. Fig. 1 is an example of one run. The bars extending down from the top of the graph indicate an occurrence of a water shortage below the nominal demand level, and the oscillating line across the middle of the graph represents the total amount of water in storage at any time over the 62-year hydrological data set.

Predicted total water-supply shortages over the course of a 62-year hydrological cycle for a range of demand levels for the current reservoir system (zero additional storage) and for an augmented reservoir system with 50, 100, or 145 kaf of additional capacity are shown in Table I. At the 210 mgd demand level, any of the additional storage capacities results in no shortages; in particular, the 1977 shortage is avoided. However, at the 240 mgd demand level, the 1977 shortage still occurs with an additional 50 kaf of storage, is ameliorated somewhat with 100 kaf of additional storage with 39 percent acceptable reductions, and is completely eliminated with 145 kaf of additional storage. At the 270 mgd demand level, additional storage eliminates most of the shortages other than that of 1977; this shortage still occurs because the reservoir system enters the year 1977 with a lower inventory than it would under a lower demand.

To summarize, water-supply accomplishments are monotonically increasing with respect to storage capacity at *any* demand level. Also, for fixed storage capacity, the ability to alleviate any particular drought-induced shortfall (and thus produce water-supply accomplishments for that year) decreases monotonically with respect to demand level. However, the number of years in which shortfalls occur (and thus the potential to produce water-supply accomplishments) increases monotonically with respect to demand level. Therefore, water-supply accomplishments are *not* necessarily monotonic with respect to demand level.

The costs for the various reservoir options are derived from estimates in the EBMUD Final EIR [7] and supporting documents. Table II lists the capital costs, initial filling costs, and estimated annual operating expenses which include refilling costs for Buckhorn and Los Vaqueros Reservoirs of specified capacity dedicated to EBMUD. For the planning horizon and approximate lifetime equivalent unit cost calculations, a three-year construction period followed by one year for initial filling of the reservoir is assumed. To establish a lower bound on unit water costs, in the perpetuity calculation, the construction time and filling time are neglected and it is assumed that benefits derive from the projects immediately.

The resulting unit costs for the range of reservoir options under consideration are presented in Table III. For a 39 percent acceptable reduction, an 80-year lifetime, a 4 percent real interest rate, and 210 mgd demand (the demand level in the table closest to the historic high of 220 mgd), the cost per af for a 145 kaf reservoir at Buckhorn Canyon is $8,265.83. Of course, the cost is lower at higher demand levels; at 300 mgd, for example, it falls to just $1,195.12. One apparent anomaly is the high cost of water at the 240 mgd demand level; however, this can be explained by the same argument presented above in describing the water-supply accomplishments. At the 240 mgd demand level, additional storage will slightly or not at all alleviate the 1977 shortage; whereas, at higher demand levels, the 1977 shortage is not alleviated but other shortages not occurring at the 240 mgd are alleviated and, at lower demand levels, the 1977 shortage is totally eliminated.

It is clear that Los Vaqueros water would be more expensive than Buckhorn water for the reservoir capacity options investigated, presumably because the terrain at Buckhorn—a relatively narrow canyon—is better suited to dam construction. On the other hand, given that Los Vaqueros will be built even without EBMUD's participation, the environmental impacts associated with EBMUD's participation in Los Vaqueros are likely to be less than those resulting from construction at both sites. Also significant are the high costs of dam extensions if a smaller capacity Buckhorn reservoir is initially constructed. If weather patterns of the recent past change significantly, the option of maintaining the Buckhorn site for a full-size reservoir, i.e., not constructing a smaller reservoir now, may be quite valuable.

The most striking feature of this analysis, the very high cost of water per af under any of the options considered, points to the difficulty and expense of attempting to solve an intermittent problem (drought) with a permanent increment to storage. As we show in the next section, an intermittent solution to an intermittent problem can be much more cost effective. In other words, if the extra water is needed only occasionally, it may be cheaper to rent than to buy.[1]

IV. COST ESTIMATION OF CONJUNCTIVE-USE/ WATER-EXCHANGE OPTIONS

Conjunctive-use options combined with water exchanges or water marketing address the intermittent nature of the drought problem. Since nearby irrigation districts, most importantly the Woodbridge Irrigation District (WID), and also some riparian users, have both groundwater reserves and surface water entitlements, the idea is to work out an agreement in which one or more of these agencies or individuals pump additional groundwater in dry years, thereby freeing some of their surface entitlements. EBMUD might then purchase the surface water. Alternatively, EBMUD might pay the costs of pumping groundwater and also subsidize groundwater recharge during normal or wet years.

Three program options are investigated in this section. The list is not all-inclusive, but a plausible range of possibilities is considered. The specific options are hypothetical at this point but are based on what we understand EBMUD is looking at in a general way. The first two options specifically address the issue of groundwater depletion in San Joaquin County, in particular groundwater depletion in the vicinity of the Mokelumne River. The conjunctive-use programs that we consider are, in essence, underground water banks with WID acting as banking intermediary. In wet years EBMUD makes deposits in the WID aquifer, and in dry years EBMUD makes withdrawals of surface water dedicated to WID at Pardee Reservoir. Over the course of the hydrological cycle, these programs must meet the stipulation that the annual groundwater deficit in Eastern San Joaquin county is not exacerbated. In both options, water-right holders downstream from Camanche Reservoir reduce their use of surface water in dry years and make up the deficit by pumping groundwater. EBMUD covers the cost of acquisition of groundwater for farmers. The two options explored here diverge only in the proposed EBMUD investment in the acquisition of water for the farmers. In the first, existing wells are utilized and EBMUD subsidizes the energy cost of pumping the water to the surface. In the second, EBMUD subsidizes in addition the cost of constructing new wells and annual maintenance. In either case, in wet years EBMUD provides excess water to the downstream agricultural users to supplant existing groundwater use and/or to enhance groundwater recharge. The third option is direct water purchases by EBMUD from downstream water-right holders (or others) in dry years.

In all of the options, both parties to the agreement are better off after the agreement is in place. In all, as we shall show, EBMUD obtains water that it can deliver to its customers during droughts at far lower cost than is possible from the reservoir options. In the first two options, the downstream right holders receive the same amount of water. The only difference is that groundwater is substituted for surface water. Additionally, the local groundwater aquifer is enhanced, reducing future pumping costs. In the third option, the farmers receive a payment for the water which they are willing to accept; farmers will only be willing to accept a payment which fully compensates them for the expected profit that will be lost if they forgo the use of some quantity of water. The local groundwater aquifer could also be enhanced in this option, if farmers choose to leave some land fallow in dry years. However, if farmers replace the transferred surface water with groundwater, the aquifer will deteriorate at a greater rate. Therefore, for the third option to be feasible given the groundwater deficit problem in San Joaquin county, some land must be left fallow in dry years.

The model is employed to assess the first two options with an additional operational criterion which supersedes all others to determine the years in which water transfers occur. The water-transfer decision criterion is based on the predicted October 1 reservoir system carryover as calculated on April 1 and is triggered by the level of Camanche Reservoir. The system goal is to keep Pardee Reservoir full. If it is predicted that Camanche will become too low and thus water will have to be drawn from Pardee, then the water transfer is instituted. The volume of the transfer is calculated to be the maximum possible up to the point where instream flow requirements will be violated. This maximum volume derives from the quantity of downstream water rights which, in turn, are based on the type of year (wet or dry) that actually does occur. The transfer volumes represent the difference between the releases that would be necessary to satisfy downstream water rights and the releases necessary only to satisfy flow requirements. These transfer volumes assume 40 percent transit losses resulting from seepage and illegal diversions. Some surface water may still be available to farmers depending on the nature of the flow requirements. In particular, if flow requirements are higher between Camanche Reservoir and agricultural diversion locations than they are further downstream, the difference may still be diverted for agricultural use. After a transfer occurs, the criteria are the same as before: incur a shortage and then allow the carryover to fall below 1.2 times annual demand.

An example of the model output is given in Fig. 2. The dark bars extending up from the bottom of the graph indicate the volume of water transfer that occurs for the given year. The total supply shortage and water-supply accomplishments over the 62-year hydrological record for the conjunctive-use program are presented in Table IV. In Table V the reduction in releases resulting from the transfer program and the actual water transfers (60 percent of release reduction) are shown. Note, in comparing Tables IV and V, that the total reduction in releases is greater than the total water-supply accomplishments. This disparity occurs because the transfers are instituted as of April 1 based on predictions of carryover volume for October 1. Therefore, the total reduction in releases may not translate directly into water-supply accomplishments if, for example, runoff or rainfall after April 1 is greater than predicted.

Table V also shows that EBMUD could meet the stipulation that the groundwater deficit problem not be exacerbated. Over the 62-year period, total water transfers are between 45.6 and 193.2 kaf. Given that EBMUD is entitled to 360 kaf annually, which is available "in most years" (EBMUD [7], p. III-16), and that annual consumption has not exceeded 240 kaf, clearly the stipulation can be met. This excess water, in fact, provides the means to supplant existing groundwater use in wet years and also for spreading operations to augment groundwater recharge should this be desired.

To complete the calculation of the unit cost of water, the costs associated with each transfer mechanism must be determined. In the first option where existing wells are used and EBMUD subsidizes the pumping costs, the following assumptions are made: (1) the approximate average depth to groundwater in the area concerned is 65 feet (derived from Brown and Caldwell [4]); (2) the average well pump energy consumption is 1.75 kilowatt hours (kwh) per af per foot raised (Brown and Caldwell [4] supporting data); (3) the average cost of energy is $0.0633125 per kwh (average summer price based on Pacific Gas and Electric (PG&E) agricultural rate schedule AG-5B, a reasonable assumption reflecting the unknown excess capacity of existing wells); and (4) planning and administrative costs of 15 percent are added (following standard engineering/economic cost accounting practice).

Resulting unit costs based on these assumptions and calculated over a 30-year planning horizon are presented in Table VI. Since expected costs and benefits are utilized and it is assumed that a shortage can occur in any given year with equal probability based on historical averages, the unit costs of water are independent of the discount rate for the first option. The striking result is that unit costs are far lower—by as much as two to three orders of magnitude—than corresponding reservoir costs.

For a 39 percent acceptable reduction, a 4 percent real interest rate, and 210 mgd demand, the cost per af under the first option is just \$5.73.

For the second option, five additional assumptions are necessary: (1) the cost of construction of a well, including pump rated at 2,000 gallons per minute, is \$25,000 (based on inquiries of local drillers and pump distributors); (2) each pump undergoes a major overhaul every five years costing \$2,500 (based on inquiries of pump distributors); (3) if each pump is operated an average of approximately 18 hours per day for 6 months of the year, then 33 wells are required to extract the maximum transfer capacity; (4) the cost of energy is \$0.03907 (based on summer off-peak rate from PG&E agricultural rate schedule AG-5B, the off-peak rate is utilized because a preliminary calculation revealed that a greater number of pumps operating in only off-peak hours is less expensive than fewer pumps operating continuously); and (5) annual operation and maintenance costs per well are, net of energy and overhaul costs, \$1,000 per well. Resulting unit costs of water based on these additional cost assumptions for the second conjunctive-use option are also presented in Table VI. In reality, an intermediate option, where wells are jointly financed and used, is likely to evolve because, in the second option, the new wells are only used in dry years. Again, however, the costs are strikingly lower—by one to two orders of magnitude—than for the reservoirs. For the low (210 mgd) demand scenario, the cost per af is \$105.75.

The third option, as noted above, is direct water purchases by EBMUD from the downstream right holders. How large a payment might they require in order to be willing to give up the water? We have just seen that one alternative to the use of the foregone surface water, namely, pumping additional groundwater, would entail costs ranging (approximately) from \$5 per af to \$105, depending on what one assumes about the need for new wells. If these cost estimates are reasonable, then an offer of not less than \$105 per af ought to be sufficient to induce substantial sales. In this case the farmer has the option of taking the money and using it to simply replace the surface water with groundwater. Of course, farmers (or districts) without access to groundwater might require a larger payment. They, and for that matter some farmers having access to groundwater, might let at least a portion of their land lie fallow for a year. Others might switch to less water-intensive crops, and still others might adopt water-saving irrigation methods. These adjustments, which do not involve additional pumping of groundwater, may in fact be socially preferred, as they would not aggravate the overdraft problem.

Here, we need to mention a recent institutional innovation. In 1991 a State Water Bank was created, for the purpose of facilitating transfers from those districts with water to sell to those who want to buy. The Bank set the prices: $125 per af to sellers, and $175 per af to buyers. It is interesting to note that the price to sellers was calculated to "yield a net income to the farmer similar to what the farmer would have earned from farming plus an additional amount to encourage the farmer to enter into a contract with a new and untried Water Bank" (DWR [6], p. 5). The price to buyers did not include conveyance costs (the energy costs of pumping the water from the Delta for State Water Project contractors, and the energy costs plus a facilities fee for noncontractors). That is, buyers would have to pay $175 per af plus conveyance costs. Assuming the Bank operates in future drought years, and the price schedule remains the same, the downstream right holders on the Mokelumne River could sell water for $125 per af. Similarly, EBMUD could buy water for $175. Conveyance costs would presumably be low, as EBMUD has a pumping station at the western edge of the Delta, where the aqueducts emerge. However, an alternative marketing arrangement might be made between EBMUD and the downstream right holders directly, i.e., without the intermediation of the Bank. A direct transfer at any price between $125 and $175 plus conveyance costs would, in theory, leave both buyer and seller better off. The opportunity for a mutually beneficial transaction will exist so long as there is a difference between the buying and selling prices set by the Bank, since the transfer is accomplished simply by leaving additional water in Pardee Reservoir.

However the conjunctive-use/water-transfer arrangement works, it is evident that the much lower unit costs of water obtained in this fashion result both from the intermittent nature of the arrangement and the disparity in cost between, on the one hand, pumping groundwater and, on the other, building and maintaining surface reservoirs for the first two options, and the disparity in the (marginal) value of water to farmers and to urban users for the third option.[2]

V. CONSUMER-SURPLUS LOSS DUE TO A PRICE-INDUCED REDUCTION IN WATER CONSUMPTION

Thus far, we have considered a variety of techniques to supplement water supplies during periods of drought. One important alternative available to water district managers—the one in fact chosen by EBMUD during recent droughts—is to reduce demand through higher prices. The associated consumer-surplus loss can be regarded as the benefit from mitigating the drought through the construction of new storage capacity or operation of a conjunctive-use/water-marketing program. No definitive study has yet been done for EBMUD, but there have been many studies of residential demand for water in other regions. It is possible to use the estimated elasticities to compute the loss in surplus associated with a price-induced cutback of 25 percent in consumption in the EBMUD service area. Table VII shows the range of estimates, on an af basis, produced using a selection of recent studies that, in our judgment, most effectively address the econometric problems.[3] The range of $40-$180 per af is below that for the reservoir options but similar to or above that for conjunctive use.[4]

VI. SUMMARY AND CONCLUSIONS

The problem posed at the outset of this paper was, how can a large urban water district best respond to a drought? What is the least-cost combination of alternatives to meet periodic shortages? We hypothesized that an answer might involve what we called nonstructural, or marketing approaches, as well as the conventional approach of adding to storage capacity by building new reservoirs. The hypothesis was tested in application to EBMUD, a large district serving 1.1 million people on the east side of San Francisco Bay.

Our findings by and large confirm the hypothesis. The cost per af of water delivered was estimated for a range of capacities for each of the new reservoir options identified in the EBMUD planning process, Buckhorn and Los Vaqueros. Buckhorn, which EBMUD would build and use by itself, appears to be somewhat cheaper than Los Vaqueros, which would be a joint project with the Contra Costa Water District (CCWD). Our more detailed cost calculations therefore were carried out for Buckhorn. Summarizing the sensitivity analyses for variants of the Buckhorn project, we found a range of costs running from about $1,000 per af to about $12,000 per af. The low cost is for a reservoir having a capacity of 145 thousand kaf, EBMUD's preferred alternative, demand at the top of the range of estimates, namely, 300 mgd, and a management regime that would, in the absence of the new reservoir, accept a shortage of up to 39 percent of normal deliveries (one of EBMUD's planning alternatives). The high cost is for a reservoir having the same capacity, demand at the low end of the range of estimates (210 mgd), and an acceptable shortage of 25 percent (EBMUD's other planning alternative). Our best estimate would be somewhere in the middle of this range, between $4,000 and $8,000 per af. It is worth noting (though that is all we do in the present study) that Los Vaqueros, though somewhat more expensive, would be preferred on environmental grounds. This is because CCWD will almost certainly proceed here regardless of EBMUD participation, so that development of the Buckhorn site would mean two impacts instead of one.

A prime alternative to reservoir construction we identified was a combination of conjunctive use and water transfer. One variant of the approach would have EBMUD pay the costs of increased groundwater pumping by downstream (from the EBMUD dams) water-right holders in dry years, and perhaps also undertake low-cost groundwater recharge activities in wet years, in exchange for the right holders' not taking some or all of their surface water entitlements, which would be left behind the dams for EBMUD use. Another variant would have EBMUD simply pay for this water, leaving to the sellers the decision on how to adjust to reduced surface water supplies. We calculated that the costs of increased groundwater pumping would range from $5 per af to $105, depending on whether new wells are required. The higher figure might also represent the sale price of the surface water, since the sellers would have the option of taking the payment and using it to replace the surface water with groundwater. The cost saving, as compared to the reservoir alternatives, is dramatic. It can be explained by the intermittent nature of the conjunctive use/transfer, the disparity in cost between pumping groundwater and building a surface reservoir, and the disparity in the (marginal) value of water to farmers and urban users.

One difficulty with the conjunctive-use/transfer approach is that it would probably not yield enough water, by itself, to compensate fully for projected EBMUD shortages. The next most promising alternative appears to be participation in the new State Water Bank, if this continues in operation. Founded in 1991, the Bank bought water for $125 per af and sold it for $175 plus conveyance costs. In fact, assuming the Bank continues, the downstream right holders would have the option of selling to it, rather than to EBMUD directly. A mutually beneficial exchange might then involve EBMUD paying the right holders some amount greater than the $125 they could get from the Bank, but less than the $175 plus conveyance costs it would have to pay the Bank for water.

Finally, we compared the costs of new storage or conjunctive-use options to the benefits: the averted consumer-surplus loss otherwise entailed by raising prices to cut back consumption in the event of a shortage. The loss in consumer surplus associated with a price increase required to achieve a 25 percent cutback falls within a range of approximately $40-$180 per af, depending on the demand elasticity. This is well below the range of reservoir cost estimates but, for the most part, above the cost of conjunctive use/water marketing. Construction of new storage capacity thus does not pass a benefit/cost test, but introduction of conjunctive use and water marketing does.

FOOTNOTES

*This research has been supported by a grant from the Water Resources Center of the University of California. We are grateful to Robert Deacon, Michael Hanemann, and three reviewers for helpful comments on an earlier draft.

[1]The California Department of Fish and Game has recommended increased flows (above current minimum levels) in the Mokelumne River to protect instream uses. Incorporating these increased flows into the model results in a substantial increase in the frequency and severity of shortages, in turn reducing the cost per af of water delivered from new storage. Some simulated results are presented in Fisher *et al.* [8]. We should note, however, that in these scenarios, reservoir levels can be drawn down nearly to zero. This is certainly unrealistic; the model's operating criteria would probably need to be altered to provide some minimum carryover.

[2]We have also studied the implications of increased flow requirements for the conjunctive-use/water-transfer arrangements. The cost per af remains about the same for the first option, and actually falls for the second, as well construction costs are spread over a larger volume of water transfers. For details, see Fisher *et al.* [8].

[3]These problems mostly derive from the nonlinear price structure produced by rising or falling block rates. Two key questions, in our judgment not fully resolved in the literature, are (1) What is the appropriate measure of price - average, marginal, or something else? and (2) How should one deal with the simultaneity that results when the price faced by consumers is affected by their choice of quantity? The now widely used Taylor-Nordin specification includes both marginal price and a variable accounting for the difference between what was paid and what would have been paid if the marginal price were constant over quantities.

[4]The change in output can be associated also with a change in producer surplus. Since we do not know the EBMUD cost curve, we do not attempt to compute this. The change in consumer surplus can, therefore, be regarded as an approximation to the welfare loss.

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TABLE I

Total Supply Reductions and Total Water Supply Accomplishments Under Various Reservoir Options

		Acceptable percent supply reduction			
		39 percent		25 percent	
Demand level	Additional storage	Total supply shortage	Total water supply accomplishment	Total supply shortage	Total water supply accomplishment
mgd	kaf				
300	0	788.6		517.6	
	50	627.6	161.0	478.0	39.6
	100	488.5	300.1	404.3	113.3
	145	332.8	455.8	238.8	278.8
270	0	377.9		251.0	
	50	232.1	145.8	75.7	175.3
	100	118.0	259.9	75.7	175.3
	145	118.0	259.9	75.7	175.3
240	0	104.9		67.3	
	50	104.9	0.0	67.3	0.0
	100	67.3	37.6	67.3	0.0
	145	0.0	104.9	0.0	67.3
210	0	65.9		58.8	
	50	0.0	65.9	0.0	58.8
	100	0.0	65.9	0.0	58.8
	145	0.0	65.9	0.0	58.8

TABLE II

Capital Costs, Initial Filling Costs, and Estimated Annual Operating and Maintenance Expenses: Various Reservoir Options

Buckhorn Reservoir			
Capacity	Capital costs	Initial fill costs	Estimated annual operating and maintenance costs
kaf	million dollars		
50	83	7	.418
100	133	12	.627
145	160	18	.794

Los Vaqueros Reservoir		
Dedicated EBMUD capacity	Capital costs	Initial fill costs
kaf	million dollars	
50	124	4
100	159	8
145	187	11

TABLE III

Buckhorn Reservoir: Unit Cost of Water Supplied (dollars per af)

		Acceptable supply reduction											
		39 percent						25 percent					
		Method of calculation											
Demand level (mgd)	Additional storage (kaf)	Perpetuity		80-year lifetime		30-year planning horizon		Perpetuity		80-year lifetime		30-year planning horizon	
		Discount rate											
		3%	4%	3%	4%	3%	4%	3%	4%	3%	4%	3%	4%
	50	1,185.32	1,540.38	1,373.21	1,719.81	2,028.82	2,316.90	4,819.16	6,262.53	5,580.99	6,989.53	8,245.19	9,415.84
300	100	1,016.46	1,332.23	1,177.22	1,476.63	1,743.82	1,992.62	2,692.32	3,502.24	3,118.62	3,911.86	4,619.63	4,657.02
	145	824.31	1,071.88	953.77	1,195.12	1,411.19	1,611.53	1,487.42	1,831.84	1,559.29	1,953.86	2,307.11	2,634.64
	50	1,308.89	1,700.97	1,516.25	1,898.95	2,240.15	2,558.21	1,201.55	1,478.87	1,261.47	1,579.88	1,863.76	2,128.36
270	100	1,173.68	1,526.75	1,359.19	1,704.90	2,013.38	2,300.63	1,920.60	2,366.20	2,015.46	2,528.08	2,985.54	3,411.44
	145	1,445.63	1,879.80	1,672.74	2,096.04	2,474.97	2,826.33	2,365.62	2,913.38	2,480.40	3,108.08	3,670.02	4,190.96
	50	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
240	100	8,112.79	10,553.39	9,402.03	11,793.35	13,927.35	15,914.50	∞	∞	∞	∞	∞	∞
	145	3,581.69	4,657.43	4,146.78	5,196.06	6,135.53	7,006.43	6,161.92	7,588.60	6,462.77	8,098.27	9,562.49	10,919.68
	50	2,895.85	3,763.22	3,354.89	4,201.64	4,956.61	5,660.46	3,582.15	4,408.98	3,761.86	4,711.27	5,557.88	6,346.92
210	100	4,628.85	6,021.15	5,360.12	6,723.35	7,939.96	9,072.85	5,725.86	7,054.36	6,010.34	7,538.86	8,903.13	10,173.12
	145	5,701.38	7,413.54	6,596.64	8,265.83	9,760.31	11,146.02	8,906.13	8,685.68	7,396.86	9,268.44	10,944.30	12,497.71

TABLE IV

Total Supply Reductions and Water Supply Accomplishments of a Conjunctive Use Option and 39 Percent Acceptable Supply Reduction Policy

Demand level	Water transfers	Total supply shortage	Total water supply accomplishments
mgd	yes or no	kaf	
300	n	788.6	
	y	585.5	203.1
270	n	377.9	
	y	300.2	77.7
240	n	104.9	
	y	104.9	0.0
210	n	65.9	
	y	0.0	65.9

TABLE V

Total Reductions in Releases and Total Water Transfers

Demand level	Number of years out of 62 water transfer to EBMUD	Total reduction in releases	Total water transfer to EBMUD (60 percent or total reductions)
mgd		kaf	
300	7	322	193.2
270	4	180	108.0
240	4	180	108.0
210	2	76	45.6

TABLE VI

Unit Cost of Water Supplied for Conjunctive Use Options Based On 39 Percent Acceptable Supply Reduction Policy Calculated for 30-Year Planning Horizon (dollars per af)

Demand level (mgd)	Option 1 Pumping energy costs		Option 2 All well costs	
			Discount rate	
	3%	4%	3%	4%
300	7.88	7.88	36.07	38.03
270	11.51	11.51	88.68	93.79
240	∞	∞	∞	∞
210	5.73	5.73	99.72	105.75

TABLE VII

Summary of Welfare Losses

Authors	Time horizon of elasticity	Change in marginal price per ccf*	Welfare loss per af due to 25 % cutback
Agthe, Billings, Dobra, and Raffiee [2]	long-run	$0.185	$40.22
	short-run	$0.317	$68.85
Agthe and Billings [1]	long-run	$0.335	$72.94
	short-run	$0.465	$101.25
Billings and Day [3]	mixed**	$0.238	$51.81
	mixed**	$0.320	$69.54
Moncur [14]	long-run	$0.482	$104.98
	short-run	$0.628	$137.03
Nieswiadomy and Molina [15]	short-run**	$0.259	$42.27
Schefter and David [17]	long-run**	$0.719	$156.80
Weber [18]	mixed	$0.827	$179.97

* Base price for January 1, 1987 = $0.666 per ccf

** Not stated by the author(s) but determined by the nature (time series or cross section) of the data.

FIGURE LEGENDS

FIG. 1. EBMUD Demand and Storage.

FIG. 2. EBMUD Demand, Storage, Transfers.

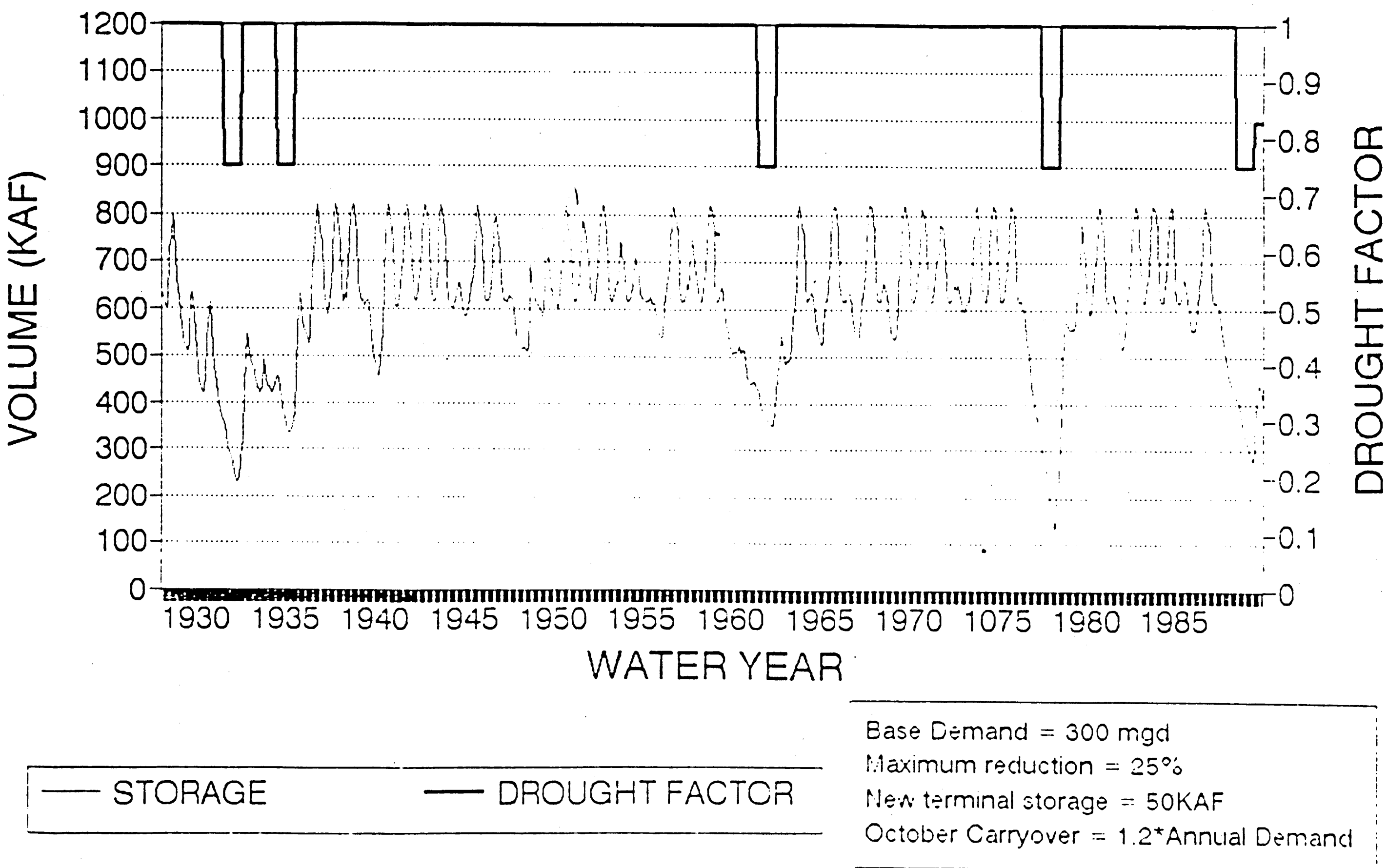

FIG. 1. EBMUD Demand and Storage.

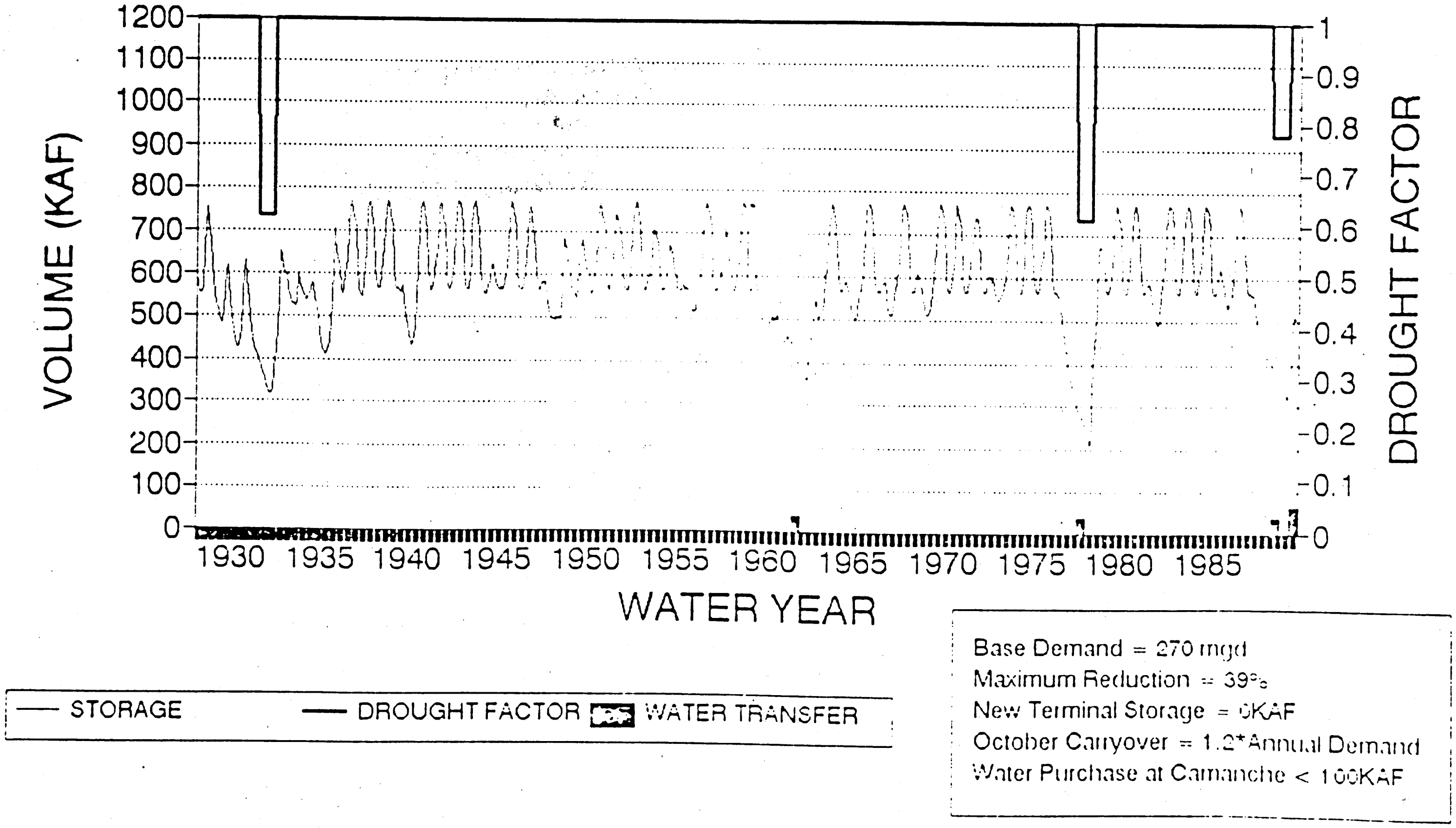

FIG 2. EBMUD Demand, Storage, Transfers.

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by

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ABSTRACT

In this paper, we examine wage changes that can accompany trade liberalization between the United States and Mexico under a North American Free Trade Agreement (NAFTA). There are two forces at work: (1) indirect links between prices and wages as described in the Stolper–Samuelson theorem, and (2) direct effects of migration on labor supplies in the two countries. Much of the debate over potential wage changes reflects views about the links between output prices and factor prices as described in the Stolper–Samuelson theorem. We demonstrate that the analytic model underlying the Stolper–Samuelson theorem does not fully describe labor market changes that will accompany NAFTA because it assumes that factors do not migrate. We extend the 2x2x2 trade model to include endowment changes and demonstrate that price changes and migration can have opposite effects on wages. One needs an empirical model with both price changes and migration to determine which wage effect dominates following trade liberalization. Using an 11-sector computable general equilibrium (CGE) model which includes the United States, Mexico, and the rest of the world, we find that migration effects generally dominate Stolper–Samuelson effects on wages. Empirically, Stolper–Samuelson effects are very small.

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1. Introduction

A major issue concerning the establishment of a North American Free Trade Agreement (NAFTA) is its impact on wages in Mexico and the United States. One argument is that the agreement will result in higher wages for unskilled labor in Mexico, but lower wages for unskilled labor in the United States.[1] This view can be derived from the Stolper–Samuelson theorem, which links changes in wages and profits to the changes in product prices caused by trade liberalization.[2] Mexico is abundant in unskilled labor relative to the U.S., and trade reform will increase Mexico's relative price of manufactured goods which it exports to the United States. According to the theorem, unskilled wages will fall in the U.S. and rise in Mexico as Mexican exports displace U.S. production of labor intensive goods.[3]

There are a number of difficulties in applying the Stolper–Samuelson theorem to the case of NAFTA. First and foremost is that the two countries are linked by more than trade in commodities. In particular, there is a long history of labor migration between Mexico and the U.S., and one would expect that such migration would be sensitive to wage changes brought about by NAFTA. When using the Stolper–Samuelson theorem, one assumes that aggregate factor supplies are constant and that shifts in labor demand curves determine wage changes. However, the effects of trade liberalization on wages can be ambiguous when there is international labor mobility which shifts the labor supply curve as well. One must account for the worker's migration decision.[4]

Second, Mexico currently strongly protects agriculture, especially the food corn sector, and agriculture uses rural labor relatively intensively. The Stolper–Samuelson effects are then more complex, with trade liberalization helping manufacturing, which uses unskilled labor intensively, and hurting agriculture, which uses rural labor intensively. As Mexico

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[1]See Leamer (1992) who argues based on the Stolper-Samuelson theorem that it is possible for wages to decline in the United States by $1000 per year. He also assumes that Mexico acquires U.S. technology and becomes much larger, comparable to Italy in the European Community.

[2]The theorem starts from a trade model with two countries, two factors (labor and capital), and two commodities. When there are more than two factors and commodities (and more goods than factors), it is more difficult to predict how factor prices will change following a change in relative prices. See Jones and Sheinkman (1977) and Ethier (1984) for a discussion of multisectoral extensions of trade theorems.

[3]An even stronger argument is provided by the factor-price-equalization theorem, which indicates that free trade in commodities can, under various strong assumptions, lead to equalization in factor prices in the trading countries, with U.S. wages falling to meet rising Mexican wages. The theorem requires the assumption that both countries have the same technology in all sectors, differing only in aggregate factor proportions. This assumption is certainly not met in the case of the U.S. and Mexico, where observed differences in production technology are enormous.

[4]In the Hecksher-Ohlin model, trade in factors can be a substitute for trade in commodities. Both can have an identical effect on wages under certain assumptions such as unrestricted factor flows and incomplete specialization under free trade. The issue becomes more complex in U.S.-Mexico relations because technologies are very different and there are migration restrictions. One does not necessarily expect migration to have the same effect on wages as the labor demand changes described in the Stolper–Samuelson theorem.

eliminates barriers to food corn imports, the rural wage should fall.[5] Given rural-urban migration within Mexico, the fall in rural wages will lead to an increase in the supply of labor to Mexican urban areas and to the manufacturing sectors. This will offset the increase in urban unskilled wages as the manufacturing sectors expand. There will also be an increase in migration pressure to the United States. The net wage changes in both the United States and Mexico will thus depend on a mix of Stolper–Samuelson and migration effects.

Finally, there are many existing distortions in both countries which will not be eliminated by NAFTA. For example, NAFTA does not affect trade barriers that Mexico and the United States maintain against other countries. In addition, there are other distortions, including existing taxes, subsidies, and intersectoral differences in wages and profit rates. All these complicate trade theory, requiring analysis of trade liberalization in a "second best" environment.

In this paper, we examine the links between trade policy and wage changes in the United States and Mexico. We develop an analytical model to demonstrate the impact of both migration and changes in output prices on wages. We show that, in theory, migration and output price changes can have offsetting effects on wages. Furthermore, we identify the crucial elasticities that affect the labor demand and labor supply shifts.

The analytical results suggest that one needs an empirical model which allows for both Stolper–Samuelson and migration effects to assess the wage changes that will accompany NAFTA.[6] We use a computable general equilibrium (CGE) model which includes both the production links between factor prices and output prices, and migration equations. When specifying migration, we assume that workers migrate between rural and urban areas in Mexico, as well as to the rural and urban labor markets in the United States to maintain constant real wage differences. We discuss how our assumptions about migration, particularly the workers' migration decision, affect migration results in the model and ultimately the wage changes in each country. In the empirical model, we also explore the sensitivity of the wage changes to parameters by calculating various response elasticities.

In addition to migration, the empirical model captures other aspects of the U.S. and Mexican economies that violate the assumptions used to analyze the links between output prices and factor prices in neoclassical trade theory. There are a number of existing distortions, such as indirect taxes and sectoral wage differentials, which are incorporated in the model. We also assume Mexico and the United States have different production technologies, in the use of both intermediate inputs and primary factors.

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[5]Implicitly there is a change in Mexico's domestic policy as well. We assumed that the government removes its price guarantee, by which it supports farm incomes by paying more than the market price. The quota on corn helps to support domestic prices, reducing the payment the government must make to satisfy the price guarantees. For more analysis of changes in Mexico's domestic policies see Burfisher, Robinson, and Thierfelder (1992).

[6]While NAFTA encompasses the United States, Mexico, and Canada, we focus on trade liberalization between the United States and Mexico only. Free trade with Mexico is the source of concern over wage changes in the United States.

Other aspects of the model qualify the results, but do not violate the assumptions needed to use the Stolper–Samuelson theorem. For example, rather than assume goods are homogenous, we maintain the Armington assumption that commodities are distinguished by country of origin. When the price of the imported variety changes, the price of the domestic good also changes, but by a lesser amount, depending on the elasticity of substitution. Consequently the output and wage responses are weaker than in a model with homogenous commodities.[7] We also capture the size differences between the two countries and Mexico's high trade dependence on the United States versus the United States' lower trade dependence on Mexico. These realistic features affect the magnitude of the links between output prices and factor prices.

The remainder of the paper is organized as follows. In section two, we present a simple general equilibrium model with migrating and non-migrating factors to analyze the links to changes in factor prices. Except for dimensionality and substitution elasticities, this analytical model closely represents our empirical model. In section three, we describe our empirical model and compare our treatment of migration to the specification in other models. Our empirical model is a three-country, 11-sector, computable general equilibrium (CGE) model in which countries are linked through trade and labor migration flows. Since most of the migration anticipated under NAFTA will come from rural Mexico, we model farm sectors in detail, giving attention to the rural and unskilled labor markets, and to the structure of agricultural programs.

In section 4, we present model simulations. The simulations are designed to explore the two mechanisms, price changes and migration, through which trade reform leads to wage changes.[8] In particular, we ask whether migration has a bigger impact on relative wages than do changes in relative output prices, the driving mechanism in the Stolper–Samuelson theorem. We find that migration generally has the dominant effect on wages under NAFTA. Finally, we create a distortion-free base run to provide a theoretically clean starting point to explore the Stolper–Samuelson effects in our empirical model. We then combine migration and a relative price change to analyze their impact in labor markets in the model with no distortions. This combination provides the best empirical representation of the theoretical model with migration and Stolper–Samuelson effects. We present conclusions in section 5.

2. Analytical Model

Jones (1965) describes a simple general equilibrium model in which a representative country produces two goods with two factors. Assuming full-employment and zero-profit conditions, he analyzes the price linkages and quantity relationships important to trade

[7]The household consumes both imports and domestic goods which are aggregated into a composite consumption commodity using a constant elasticity of substitution equation. Likewise, there is a constant elasticity of transformation by which domestic output is converted into goods for either domestic consumption or export. Labor and capital are used to produce the domestic output.

[8]In addition to Stolper-Samuelson and migration effects, terms-of-trade effects in the presence of economies of scale (for the United States, at least) have substantial effects on factor prices. See Brown (1993). We do not account for economies of scale in this paper.

theory. He demonstrates that changes in relative wages depend on changes in relative output prices and that changes in relative output depend on changes in both relative prices and the relative endowment. These results are summarized in equations (1) and (2).

$$(\hat{w} - \hat{r}) = (\hat{P}_1 - \hat{P}_2)\frac{1}{|\Theta|} \tag{1}$$

$$(\hat{X}_1 - \hat{X}_2) = \frac{1}{|\Lambda|}(\hat{L} - \hat{K}) + \frac{(\delta_L + \delta_K)}{|\Lambda|\,|\Theta|}(\hat{P}_1 - \hat{P}_2) \tag{2}$$

where a ^ indicates the percentage change in the variable and the other parameters are defined below.

w = the payment to labor
r = the payment to capital
X_1 = output of good one
X_2 = output of good two
P_1 = price of good one
P_2 = price of good two
L = aggregate labor supply
K = aggregate capital supply.

Equation (1) links changes in factor returns to changes in output prices. Equation (2) links output changes to changes in both factor endowments and relative output prices.

Relative factor intensity, in the value sense, reflects the allocation of revenue to labor and capital in production. It is represented in the determinant of the matrix of factor payment shares by sector:

$$|\Theta| = \theta_{L1}\theta_{K2} - \theta_{L2}\theta_{K1} \tag{3}$$

where $\theta_{i,j}$ i = L, K; j = 1, 2 indicates the share of revenue from production of good j that is allocated to factor i. When $|\Theta| > 0$, good one is relatively labor intensive in terms of the share of revenue allocated to labor.

Likewise, one can represent physical factor intensity in terms of the share of the endowments of labor and capital allocated to each sector The determinant of the matrix of factor endowment shares is given by:

$$|\Lambda| = \lambda_{L1}\lambda_{K2} - \lambda_{L2}\lambda_{K1} \tag{4}$$

where $\lambda_{i,j}$, i = L, K; j = 1, 2 indicates the share of the endowment of resource i used in sector j. When $|\Lambda|$ >, 0 good one is relatively labor intensive.

Factor substitution in production allows producers to substitute away from the factor whose price increases. For example, as the relative wage increases, both sectors become relatively more capital intensive. The following parameter represents the producer savings from switching to less labor intensive production techniques when the relative wage increases and output does not change:

$$\delta_L = \lambda_{L1}\theta_{K1}\sigma_1 + \lambda_{L2}\theta_{K2}\sigma_2 \tag{5}$$

Likewise, there are savings when producers switch to less capital-intensive production techniques when the relative payment to capital increases and output does not change:

$$\delta_K = \lambda_{K1}\theta_{L1}\sigma_1 + \lambda_{K2}\theta_{L2}\sigma_2 \tag{6}$$

where σ_j is the production response to a relative factor price change in sector j and $\theta_{i,j}$ and $\lambda_{i,j}$ are defined above; δ_i (i = L, K) is positive since all components are positive.

Both relative price changes and labor supply changes can affect relative factor returns. When the relative price changes, there are indirect links to wages due to output changes. The change in production generates a change in the demand for labor. For example, when output of the labor intensive good expands, there is a net increase in labor demand.[9] When the relative endowment changes as well, there is a direct effect on wages as the supply of labor changes. One can summarize these labor demand and labor supply effects using Jones' equations. Substituting equation (1) into equation (2) and rearranging, one finds that:

$$(\hat{w} - \hat{r}) = [(\hat{X}_1 - \hat{X}_2) - \frac{1}{|\Lambda|}(\hat{L} - \hat{K})]\frac{|\Lambda|}{(\delta_L + \delta_K)} \tag{7}$$

To incorporate the effects of changes in relative output prices on relative factor prices, one needs to know how responsive the relative output level is to a relative price change. Essentially, one must specify the shape of the production possibilities frontier (PPF) for goods one and two. The transformation elasticity is defined as:

$$\Omega = -\frac{d(X_1/X_2)/(X_1/X_2)}{d(P_1/P_2)/P_1/P_2)} \tag{8}$$

In Jones' notation, the expression becomes:

[9]Both sectors do become relatively more capital intensive as the relative wage increases.

$$\Omega = -\frac{(\hat{X}_1 - \hat{X}_2)}{(\hat{P}_1 - \hat{P}_2)} \tag{9}$$

Using equations (1) and (2), which summarize technology in Jones' model, and assuming no endowment change, one can define the transformation elasticity as:

$$\Omega = -\frac{(\delta_L + \delta_K)}{|\Lambda|\ |\Theta|} \tag{10}$$

When there are no labor market distortions, which appear as exogenous wage differentials by sector, Ω is negative because the sign of $|\Lambda|$ equals the sign of $|\Theta|$ and δ_L and δ_K are positive by definition.[10]

Substituting equation (10) into equation (7), one can describe both the price effect, which works through indirect links, and the migration effect on relative factor returns.[11]

$$(\hat{w} - \hat{r}) = [-\Omega(\hat{P}_1 - \hat{P}_2) - \frac{1}{|\Lambda|}(\hat{L} - \hat{K})]\frac{|\Lambda|}{(\delta_L + \delta_K)} \tag{11}$$

When good one is relatively labor intensive, $|\Lambda|$ is positive. Using equation (11), when the relative price of good one (the labor intensive good) increases, the relative wage increases, as specified in the Stolper–Samuelson theorem. When the labor supply increases, and prices are not held constant, there is downward pressure on wages. The wage change in response to an endowment change is independent of the relative factor intensity of good one and good two.

To compare the magnitude of the two changes, compare the coefficient on the percent change in prices to the coefficient on the percent change in the endowment. After simplifying, the coefficient on the relative price change reduces to:

$$\frac{1}{|\Theta|} \tag{12}$$

When there is no endowment change, this coefficient describes the links between factor prices and output prices stated in the Stolper–Samuelson theorem. The more extreme the differences in factor intensities, the bigger the relative factor price change following a change in output prices. The coefficient on the relative endowment change reduces to:

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[10]Jones (1971) describes conditions such that the sign of $|\Lambda|$ does not equal the sign of $|\Theta|$. Essentially, $\Omega < 0$. See Thierfelder (1992) for a discussion of Jones' model with factor market distortions and an extension to include efficiency wage sectors which justify the presence of wage differentials.

[11]One can show that equation (11) reduces to equation (1) when the endowment is constant.

$$- \frac{1}{\delta_L + \delta_K} \tag{13}$$

The coefficient indicates the change in factor intensity in each sector following an endowment change, when output prices can vary. This coefficient reduces to zero when output prices are held constant.[12] In this case, relative factor prices do not change and one can derive the Rybczynski results.

A migration change essentially is an endowment change in Jones' specification. We assume workers migrate in response to relative wage differences. To determine migration levels, one must evaluate the labor market equilibrium in each country as well as the migration equation. The system of labor demand and labor supply equations by country, including migration between countries, is solved simultaneously. Labor demand in each country is a function of the output price and the relative wage. The vertical labor supply curve shifts when labor migrates. In theory, one might expect labor to migrate in response to wage differentials and move until wages are equal in both countries.[13] Studies of wages in the United States and Mexico suggest that existing wage differentials will persist under trade liberalization, so we assume labor migrates to maintain a constant wage differential between the two countries.[14]

To identify sources of the wage change in a simple general equilibrium model with migration, one can consider the forces affecting labor supply and demand independently. Labor demand shifts depend on changes in the relative output price given factor intensities in production. For example, an increase in the output of the labor intensive good means that labor demand will increase. The magnitude of the labor demand shift depends on the output elasticity to a relative price change and on the elasticity of labor demand to an output change. Given a fixed aggregate labor supply, the wage will increase following an increase in the price of the labor intensive good.

When one allows labor to migrate, and assumes workers migrate to maintain fixed wage differentials, labor moves into the country that experiences the wage increase under no migration. The increase in labor supply reduces the wage. Since the supply curve shifts, the wage elasticity of labor demand matters in determining wage changes in the home country. Migration occurs until the initial wage differential has been re-established. When

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[12]From equations (9) and (10), one can show that:

$$\frac{1}{\delta_L + \delta_K} = \frac{(\hat{P}_1 - \hat{P}_2)}{(\hat{X}_1 - \hat{X}_2)}$$

Equation (13) reduces to zero when relative output prices are held constant.

[13]See Mundell (1957) for further discussion.

[14]For example, Reynolds (1992) projects a wide gap between relative wages across the two countries regardless of forces that would promote convergence. Levy and van Wijnbergen (1993) assume that labor migrates within Mexico to maintain a fixed real income differential.

the labor demand curve is inelastic, a small amount of migration is needed to affect wages and restore the initial differential. More migration occurs when the labor demand curves in each country are more elastic.

As summarized in equation (11), wage changes become indeterminate when one allows migration in conjunction with price changes in the analytical two-country model. One needs to specify in more detail what motivates migrants. To determine the wage changes that will accompany NAFTA, one must use an empirical model which accounts for trade and migration flows. In an empirical model, the magnitude of the labor demand and labor supply changes will depend on the elasticities implicit in the observed base-year equilibrium. From the base data for each country, one can calculate empirically the output elasticity to a price change, the elasticity of labor demand to output changes, and the wage elasticity of labor demand by sector from data on the United States and Mexico.

3. Three–Country CGE Model

3.1 Core FTA-CGE Model

Our empirical model builds on earlier models of the U.S.–Mexico free trade area (FTA) by Hinojosa-Ojeda and Robinson (1992) and Robinson *et al.* (1993).[15] The FTA-CGE model is an 11-sector, three-country, computable general equilibrium model. The production and consumption behavior in the United States and Mexico is modeled in detail, and the two countries are linked through trade and migration flows. There are import demand and export supply equations to represent the interaction between the rest of the world and either the United States or Mexico. Table 1 presents aggregate data for the United States and Mexico, as well as the trade flows between them; the data are used to generate the benchmark or base solution of the FTA–CGE model. Mexico is a much smaller and poorer economy and has a higher share of trade in GDP than the U.S. The U.S. market accounts for over 60% of Mexican exports, while Mexico buys only about 5% of total U.S. exports. As is typical of a developing country, rural labor is a large share of the Mexican labor force: 23.8% compared to 1.1% for the U.S.

Table 2 shows the sectoral structure of GDP, employment, and trade for the two countries, as well as existing trade barriers. The model's 11 sectors include four farm and one food processing sector. The food corn sector refers to corn used for human consumption. In Mexico, this includes white corn, the small proportion of domestic yellow corn used for food, and No. 2 yellow corn imports from the U.S., which are assumed to enter food use. In the U.S., the food corn sector refers to its world exports of No. 2 yellow corn. The program crops sector is composed of the other crops eligible for U.S. deficiency payments — feed corn, food grains, soybeans, and cotton. Other agriculture includes livestock, poultry, forestry and fishery, and other miscellaneous agriculture. The fruits and vegetables sector in Mexico includes beans, a major food crop.

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[15]The latter provides a complete listing of the equations of the model. The FTA-CGE model is implemented using the GAMS software, which is described in Brooke, Kendrick, and Meeraus (1988).

Table 1 — Comparative Aggregate Data, U.S. and Mexico

	Mexico	U.S.
GDP ($US billions, 1988)	175.0	4485.7
Per Capita GNP ($US, 1988)	1,760	19,990
<u>Trade flows (percent of GDP)</u>		
Total exports	16.5	7.9
Exports to partner	10.1	0.4
Total imports	5.8	11.6
Imports from partner	4.3	0.9
<u>Employment structure (percent)</u>		
Rural labor	23.8	1.1
Urban unskilled labor	14.1	17.7
Urban skilled labor	37.1	48.5
White collar workers	25.0	32.7
Total	100.0	100.0
Population, ages 15-64 (millions)	49	162
Total population (millions)	84	246

<u>Sources</u>:
Per capita GNP, and population data refer to 1988 and come from World Bank, <u>World Development Report 1990</u>. Mexico's GDP is calculated using official exchange rates. Employment data are unpublished data from Dolores Nieto, Colegio de Mexico. Trade and GDP data are from U.S. and Mexican social accounting matrices developed by the Economic Research Service, U.S. Department of Agriculture (USDA/ERS).

The base year for Mexico is mostly 1988.[16] The U.S. uses a 1987 base year because of the severe contraction of agricultural output following the 1988 drought. Bilateral trade flows are from 1988. Because of the volatility in U.S. 1987-88 agricultural output, the model follows Adams and Higgs (1986) in the use of a "synthetic" base year for the U.S., imposing 1988 U.S.–Mexican bilateral trade flows on a 1987 base U.S. economy.

The model is in the theoretical tradition of neoclassical, trade-focused, CGE models.[17] Each sector produces a composite commodity that can be transformed according to a constant elasticity of transformation (CET) function into a commodity sold on the domestic market or

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[16]The data base is documented in Burfisher, Thierfelder, and Hanson (1992). Unpublished data on Mexican employment were compiled by Dolores Nieto, Colegio de Mexico.

[17]Robinson (1989) and de Melo (1988) survey single-country, trade-focused, CGE models.

Table 2 — Sectoral Structure of U.S. and Mexican Economies, Base Solution

	Sectoral shares (percent) in:								Bilateral import barriers	
	GDP		Employment		Imports		Exports			
Commodity	U.S.	Mexico	U.S.	Mexico	U.S.	Mexico	U.S.	Mexico	U.S.	Mexico
Food corn	0.0	0.7	0.0	6.3	0.9	0.0	0.3	0.0	0.0	45.0
Program crops	0.5	1.1	0.4	5.3	2.9	0.0	3.3	0.1	0.0	12.9
Fruits/vegetables	0.2	1.1	0.4	3.5	0.1	0.6	0.4	3.0	13.2	12.5
Other agriculture	0.8	5.1	1.4	8.6	1.3	1.7	0.4	3.8	0.6	8.9
Food processing	1.7	6.2	1.5	2.5	5.2	2.2	2.9	3.6	3.8	8.2
Other light mfg.	4.5	5.5	5.1	2.7	4.3	15.0	7.0	6.0	4.7	8.1
Oil and refining	2.2	2.9	0.5	0.5	5.0	12.0	2.7	10.2	1.5	8.8
Intermediates	5.6	8.2	4.5	3.2	16.8	13.0	14.0	12.3	2.2	8.0
Consumer durables	1.9	2.5	1.7	0.8	14.5	28.3	10.0	18.7	1.8	12.0
Capital Goods	5.2	3.4	4.9	2.2	25.6	24.6	31.8	12.0	3.6	12.7
Services	77.4	63.3	79.6	64.4	23.5	2.6	27.5	30.3	0.0	0.0

Notes:
Bilateral import barriers are the combined rate of trade-weighted tariffs and tariff equivalents of quotas on trade between Mexico and the U.S.
Percent composition columns sum to 100%, except for rounding error. Data are for 1987 for U.S. and 1988 for Mexico.

Sources:
Burfisher, Thierfelder, and Hanson (1992).

into an export. Output is produced according to a constant elasticity of substitution (CES) production function in primary factors, and fixed input-output coefficients for intermediate inputs. The model simulates a market economy, with prices and quantities assumed to adjust to clear markets. All transactions in the circular flow of income are captured. Each country model traces the flow of income (starting with factor payments) from producers to households, government, and investors, and finally back to demand for goods in product markets.

Consumption, intermediate demand, government, and investment are the four components of domestic demand. Consumer demand is based on Cobb-Douglas utility functions, generating fixed expenditure shares. Households pay income taxes to the government and save a fixed proportion of their income. Intermediate demand is given by fixed input-output coefficients. Real government demand and real investment are fixed exogenously.

We use import demand equations based on the Almost Ideal Demand System (or AIDS).[18] The AIDS function is a flexible functional form that can generate arbitrary values of pairwise substitution elasticities at a given set of prices, and also allows expenditure elasticities different from one. It generates more realistic empirical price behavior than does the more common CES formulation.

The model includes six primary factors and associated factor markets: rural labor, urban unskilled labor, urban skilled labor, professional labor, capital, and agricultural land. Full employment for all labor categories is assumed and aggregate supplies are set exogenously. The model can incorporate different assumptions about factor mobility, including labor migration (discussed below). In the experiments reported here, we assume that agricultural land is immobile among crops, but that all other factors are intersectorally mobile, including capital. Note, however, that labor markets are segmented. Rural labor does not work in the industrial sectors, and urban labor does not work in agriculture. These labor markets are linked through separate migration equations. The results should be seen as reflecting adjustment in the long-run, with capital able to leave the agricultural sectors.

Agricultural trade policies and domestic farm programs are modeled explicitly, including tariffs, import quotas, input subsidies to producers and processors, Mexico's tortilla subsidies to low income households, and the U.S. deficiency payment program. Deficiency payments and the tariff-equivalents of quotas are determined endogenously and are not treated as fixed *ad valorem* wedges.

There are three key macro balances in each country model: the government deficit, aggregate investment and savings, and the balance of trade. Government savings is the difference between revenue and spending, with real spending fixed exogenously but revenue depending on a variety of tax instruments. The government deficit is therefore determined endogenously. Real investment is set exogenously, and aggregate private savings is

[18]The AIDS specification in this model draws on work by Robinson, Soule, and Weyerbrock (1991).

determined residually to achieve the nominal savings-investment balance.[19] The balance of trade for each country (and hence foreign savings) is set exogenously, valued in world prices.

Each country model solves for relative domestic prices and factor returns, which clear the factor and product markets, and for an equilibrium real exchange rate which brings aggregate export supply and import demand into balance, given the exogenous aggregate balance of trade in each country. The model determines two equilibrium real exchange rates, one each for the U.S. and Mexico, which are measured with respect to the rest of the world. The reported exchange rate is the price-level-deflated exchange rate; it is the nominal exchange rate deflated by a domestic price index. The cross rate (U.S. to Mexico) is implicitly determined by an arbitrage condition. In this class of models, which include a non-traded domestic variety of each commodity, the real exchange rate is essentially the ratio of the prices of non-tradable to tradable goods in each country.[20] Since commodities are valued in local currency (pesos in Mexico and dollars in the United States), prices within each country are normalized to a country-specific domestic price index.[21] The numeraire goods are aggregates of the non-traded goods in each country. This specification is convenient for a model in which the commodities are not homogenous.

We do not specify production and consumption details for the rest of the world. Instead we specify world demand and supply functions for traded goods, largely by assuming fixed world prices.[22] In effect, the model specifies sectoral export supply and import demand functions for each country, and solves for a set of world prices that achieve equilibrium in world commodity markets. At the sectoral level, in each country, demanders differentiate goods by country of origin and exporters differentiate goods by country of destination.

Four types of elasticity parameters are used in the model. The production specification requires sectoral elasticities of substitution among primary factors. The CET export supply functions require elasticities of transformation between goods sold on the home and export markets. The AIDS import demand functions require sectoral income elasticities and substitution elasticities for home goods and for goods from each import source. We have drawn on estimates and "guesstimates" from various studies, including Hinojosa and Robinson (1992); Hanson, Robinson, and Tokarick (1993); and Reinert and Shiells (1991).[23]

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[19]Enterprise savings rates are assumed to adjust to achieve the necessary level of aggregate savings in each country.

[20]See Devarajan, Lewis, and Robinson (1993) for a further discussion of the real exchange rate in CGE models.

[21]This specification, by which we hold the domestic price index constant in the United States and Mexico, is used in other multi-country CGE models. See for example, Reinert, Roland-Holst, and Shiells (in this volume).

[22]In two sectors, corn and program crops, we assume downward sloping world demand curves for U.S. exports, and hence world prices are not fixed for these sectors.

[23]In lieu of econometric estimation, one can do sensitivity analysis to check for the robustness of the model results using alternative elasticity parameters. See Burfisher, Robinson, and Thierfelder (1992) for a discussion of model sensitivity to the elasticities used in the food corn sector, a major source of migrating labor. See Burfisher (1992) for a discussion of model sensitivity to parameters in all sectors.

3.2 Migration

In the FTA-CGE model, we specify three migration flows: rural Mexico to rural U.S. labor markets, urban unskilled Mexico to urban unskilled U.S. labor markets, and internal migration within Mexico from rural to unskilled urban labor markets.[24] In equilibrium, international migration adjusts to maintain a specified ratio of real average wages, $wgdf_{mig}$, for linked labor markets in the two countries, measured in a common currency. Similarly, internal migration in Mexico maintains a specified ratio of average real wages between the rural and unskilled urban markets. The international migration equation is:

$$WF_{mig,mx} = wgdf_{mig} \cdot WF_{mig,us} \cdot \frac{EXR_{mx}}{EXR_{us}} \qquad (14)$$

where the index *mig* refers to the migration flow, $WF_{mig,k}$ is the real average wage, and EXR_k is the exchange rate. The domestic labor supply in each skill category in each country is adjusted by the migrant labor flow. In the internal migration equation for Mexico, rural and urban workers compare wages within Mexico, and there is no exchange rate effect.

Migration flows generated by the FTA-CGE model refer to changes in migration from a base of zero. They should be seen as additional migration flows due to the policy change, adding to current flows.[25] Current migration flows are substantial, both within Mexico and between Mexico and the U.S.[26] In addition, the net migration flows generated by the model represent workers, or heads of households. In recent years, a substantial share of migrants have been family members. The model thus probably understates total increased migration due to a policy change, since family members will tend to migrate with workers.

Other empirical studies of U.S. trade with Mexico also include migration. For example, Levy and van Wijnbergen (1993) allow migration between rural and urban unskilled labor markets to maintain a fixed differential, as we do in our model. They model Mexico alone and do not account for migration to the United States. In addition, they use a utility based measure of real wage differences, and account for transfer income and land rent in rural income. In this model, we assume only a wage comparison. In a larger version of this model, which includes 28 sectors and distinguishes irrigated and non-irrigated land, we also account for land rent in rural household income.[27] The correct differential in the

[24]There is no internal migration between the urban and the rural labor market in the United States, but the two labor markets are implicitly linked, given the other migration flows.

[25]Since NAFTA does not specify changes in migration laws, these numbers should be interpreted as changes in migration pressure; they indicate an increase in the potential for illegal immigration.

[26]Various researchers have placed the net increase of undocumented Mexican immigrants in the U.S. to be around 100,000 a year during the 1980s. See Bean, Edmonston, and Passel (1990).

[27]See Burfisher, Robinson, and Thierfelder (1992). We define real wages in terms of a single aggregate price index in each country. Levy and van Wijnbergen (1993) account for differences in consumption patterns across household groups.

migration equation depends on the workers' motivation. If workers migrate to remit income, utility measures based on personal consumption would not be appropriate. Instead, one would want a wage differential that incorporates exchange rate changes.

In a simple model of two goods and two factors, Hill and Mendez (1984) consider the effects of trade liberalization on the wage differential between the United States and Mexico. Using a migration elasticity, they then compute the amount of migration that would accompany the new wage differential. Our specification includes the migration effect and the price effect on wages simultaneously.

4. Model Results

4.1 Scenarios

As summarized in table 3, we specify five scenarios which are designed to explore wage and migration changes that accompany bilateral tariff and quota elimination between the United States and Mexico, but with no changes in domestic policies.[28] In the first three scenarios, we make alternative assumptions about labor migration to decompose the effects of relative price changes and migration on wages. In the scenario with full migration, we consider the sensitivity of migration to different model assumptions, focusing on the role of exchange rates and fixed wage differentials.

In scenarios 4 and 5, we explore the relationship between international migration and Stolper–Samuelson effects in our empirical model. We remove distortions from the empirical model to create a theoretically clean base, consistent with the assumptions used in the Stolper–Samuelson theorem. In scenarios 4a and 4b, we look for Stolper–Samuelson wage effects following the introduction of various tariffs, which cause relative output price changes in Mexico and the U.S. In scenario 5, we introduce both a U.S. tariff and international migration into the distortion-free model, showing the dominance of migration effects on wages over Stolper–Samuelson effects under NAFTA.

4.2 Labor Migration and the Effects of NAFTA

In scenario 1, we consider bilateral trade liberalization between the United States and Mexico when there are no migration flows, in effect restricting rural labor to the farm sectors. To evaluate migration effects, we extend scenario 1 and allow internal migration within Mexico between rural and urban unskilled labor markets in scenario 2. Finally, in scenario 3 we allow both internal Mexican migration and international migration flows between the rural and urban unskilled labor markets in Mexico and the United States, in conjunction with bilateral trade liberalization.

[28]See Robinson, *et al.* (1993); Burfisher, Robinson, and Thierfelder (1992); and Burfisher (1992) for analysis of the economic effects and policy implications of NAFTA, using the FTA-CGE model. In these papers, we consider a wide range of policy scenarios. For example, we consider changes in agricultural policies, particularly the elimination of Mexico's input subsidies to agriculture. We find substantially higher migration flows when Mexico eliminates domestic support in conjunction with NAFTA, as opposed to trade liberalization alone.

Table 3 — Description of Scenarios

No.	Scenario	Description
1.	Free trade, no migration	Remove all bilateral tariffs and quotas.
2.	Free trade, internal Mexican migration	Scenario 1 plus allow rural-urban migration in Mexico.
3.	Free trade, international migration	Scenario 1 plus both rural-urban migration in Mexico, and labor migration between the U.S. and Mexico.
4a.	Stolper–Samuelson effects	Effects of a Mexican tariff in a distortion-free base model in which we remove factor payment differentials, sectoral differences in indirect and value added taxes, and bilateral tariffs and quotas. High transformation and substitution elasticities to minimize the effect of the Armington Assumption. No farm programs in either Mexico or the United States.
4b.	Stolper–Samuelson effects	Effects of a U.S. tariff in a distortion-free base model described in 4a.
5.	Stolper–Samuelson and migration	Migration and a U.S. tariff in a distortion-free base model described in 4a.

We find that international migration reverses the effects of NAFTA on rural wages in the U.S. and Mexico (table 4). With no migration, liberalization of the highly protected farm sectors causes Mexico's rural wage to decline over 5%, while the U.S. rural wage rises 0.8%, consistent with the Stolper–Samuelson theorem. Increasing the mobility of rural labor diminishes the effects of falling Mexican farm prices on rural wages. When we assume labor can migrate between rural and urban areas in Mexico, Mexican rural wages decline by only 2%. As 180,000 workers migrate to urban areas, the decline in the labor supply partially offsets effect of a decline in labor demand on the rural wage. Urban unskilled wages in Mexico decline by 2%, despite the increase in labor demand as output expands under NAFTA. When we do not allow migration, Mexico's urban unskilled wages rise 0.4%, reflecting the increase in the demand for labor as the manufacturing sectors expand. In Mexico's urban labor market, the migration effects dominate the labor demand changes.

When we assume there is international migration, 360,000 rural Mexican workers (6% of the farm labor force) migrate to either urban Mexico or to the U.S. This decline in the supply of rural workers causes Mexican rural wages to rise by 1.0%, dominating the agricultural price decline which works to reduce farm wages. In the U.S., the increase in rural labor supply causes rural wages to fall by 1.0%, despite the upward pressure of rising farm prices on rural wages.

Table 4 — Real Factor Returns under a U.S.-Mexico FTA, with and without Migration, Percent Change from Base

	No migration	Internal migration	Internal and international migration
Migration		--- 1,000 persons ---	
U.S. rural	0	0	20
U.S. urban unskilled	0	0	400
Mexican rural-urban	0	180	340
U.S. factor prices		--- Percent change from base ---	
Rural	0.8	0.9	-1.0
Urban unskilled	-0.1	-0.1	-1.0
Union	0.0	0.0	0.1
Professional	0.0	0.0	0.0
Agric. land	0.5	0.5	0.7
Capital	-0.1	-0.1	0.0
Mexican factor prices			
Rural	-5.3	-1.9	1.0
Urban unskilled	0.4	-1.9	1.0
Union	0.6	0.6	0.4
Professional	0.5	0.5	0.3
Agric. land	-6.6	-6.7	-7.6
Capital	0.2	0.3	0.2

With international migration, the changes in the labor supply in Mexico's urban labor market depend on the net effect of labor entering from the rural areas and labor leaving to the U.S. urban areas. Under NAFTA, migration to the United States dominates and the Mexican urban labor supply declines. The decrease in labor supply and the increase in labor demand associated with output changes following NAFTA complement each other in terms of the effect on the urban wage in Mexico. The Mexican urban wage increases 1%, compared to an increase of 0.4% when only labor demand changes affect the wage in scenario 1.

In the United States, the urban wage declines further with international migration than in scenario 1, with no migration. With no migration, the decline in the demand for urban unskilled labor (following the price changes associated with NAFTA) reduces the urban unskilled wage by 0.1%. This Stolper–Samuelson effect is quite small. The increase in the supply of urban unskilled labor, in the scenario with migration, reduces the urban unskilled wage further. It declines by 1.0% in the United States—still small, but an order of magnitude larger than the Stolper–Samuelson effect.

Although the wage effects of NAFTA are dominated by migration flows, the effects of NAFTA on prices and factor demand are consistent with changes described in the Stolper–Samuelson theorem. The magnitude of these changes are summarized in table 5.

Table 5 — Price, Output, and Labor Demand Effects of an FTA with Internal and International migration (Scenario 3), Percent Change from Base

	Output price	Output	Labor demand: rural	Labor demand: urban unskilled
United States	--- Percent change from base ---			
Food corn	3.1	6.7	10.2	na
Program crops	0.1	0.7	2.0	na
Fruit/vegetables	-0.1	0.4	1.6	na
Other agriculture	0.0	0.2	1.5	na
Food mfg.	0.1	0.1	na	2.2
Other light mfg.	0.1	0.1	na	2.2
Oil/gas	0.2	0.0	na	2.1
Intermediates	0.0	0.2	na	2.3
Consumer durables	0.0	0.2	na	2.2
Capital goods	0.0	0.1	na	2.2
Services	0.0	0.1	na	2.1
Mexico				
Food corn	-4.7	-13.1	-17.4	na
Program crops	-1.2	-5.5	-7.4	na
Fruit/vegetables	1.3	5.2	5.5	na
Other agriculture	0.2	0.0	-0.6	na
Food mfg.	0.1	-0.5	na	-1.9
Other light mfg.	0.3	0.6	na	-0.9
Oil/gas	1.7	0.0	na	-1.5
Intermediates	0.4	1.4	na	-0.1
Consumer durables	0.2	4.7	na	3.1
Capital goods	0.3	2.8	na	1.3
Services	0.2	-0.3	na	-1.7

Notes: Scenario 3 assumes removal of bilateral tariffs and quotas, and internal and international migration. NA denotes that the factor is not employed in that sector.

In Mexico, the most dramatic changes occur in the food corn sector, which has the highest initial protection, a tariff equivalent of 45%.

Aggregate effects of NAFTA are reported in table 6. Unlike the case of factor prices, aggregate results of NAFTA are almost unchanged by varying the migration assumptions in scenarios 1–3. For the U.S., there are no measurable aggregate efficiency gains from trade liberalization with Mexico in scenarios 1 and 2, and migration largely accounts for the small

Table 6 — Aggregate Effects of a U.S.-Mexico FTA, with and without Migration, Percent Change from Base

	Scenario 1: No migration	Scenario 2: Internal migration	Scenario 3: Internal and international migration
	--- Percent change from base ---		
Real GDP - U.S.	0.0	0.0	0.1
Real GDP - Mexico	0.5	0.6	0.3
Exchange rate - U.S.	0.0	0.0	0.0
Exchange rate - Mexico	2.1	2.2	2.0
U.S. exports to Mexico	8.4	8.7	8.6
U.S. exports to rest	0.0	0.0	0.2
U.S. imports from rest	0.1	0.1	0.2
Mexican exports to U.S.	5.0	5.0	5.1
Mexican exports to rest	4.7	5.0	4.6
Mexican imports from rest	-0.6	-0.6	-0.8
Farm program expenditure:			
U.S.	-0.7	-0.7	-0.5
Mexico	-1.5	-1.9	-2.6
Terms of trade:	--- Index, base = 1.0 ---		
U.S. to Mexico	1.01	1.01	1.01
U.S. to world	1.00	1.00	1.00
Mexico to U.S.	0.99	0.99	0.99
Mexico to world	0.99	0.99	0.99

Notes: The "real exchange rate" is the price-level deflated exchange rate using the GDP deflator. A positive change represents a depreciation. Exports are valued at world prices (in dollars).

increases in GDP in scenario 3. In Mexico, real GDP increases slightly in all scenarios, but is lowest in scenario 3, because labor migration to the U.S. reduces its labor endowment.

Bilateral trade increases significantly in all three NAFTA scenarios. For the U.S., NAFTA is trade creating in all three scenarios, with imports rising from both Mexico and the rest of the world. For Mexico, NAFTA results in very small trade diversion as imports from the United States replace imports from the rest of the world.

Both countries' farm program expenditures fall under all three scenarios. In the U.S., the decline in expenditure reflects a decline in the deficiency payment because farm prices rise with export growth to Mexico.[29] In Mexico, farm program expenditures fall because of the decline in farm output. Bilateral trade expansion occurs with virtually no effect on the international terms of trade.

Sectoral results are presented in table 7. Bilateral export growth of both countries under NAFTA is highest in the farm sectors, reflecting the fact that both countries have provided relatively high trade protection to their agriculture. Agricultural trade growth is accomplished mostly through changes in crop mix, with little change in total farm output in either Mexico or the U.S. The net effect of labor migration for the agricultural sectors is to shift farm production from Mexico to the U.S., and to increase U.S. farm exports to Mexico.

4.3 Sensitivity of Migration Results to Model Specification

Since migration effects largely determine the wage changes following NAFTA, we explore the sensitivity of migration to our specification. We do sensitivity experiments against scenario 3, which includes bilateral trade liberalization and international migration.

In the model, exchange rates can affect migration because we assume labor evaluates wages in a common currency. Totally differentiate the migration equation, equation (14):

$$\widehat{WF}_{MX} = \widehat{wgdf} + \widehat{WF}_{US} + \widehat{exr}_{MX} - \widehat{exr}_{US} \tag{15}$$

where a ^ designates percent change. It is possible that, while real wages measured in a common currency are equated, wages can grow at different rates measured in the domestic currency. One might even observe migrants moving from a labor market where real wages (in domestic prices) are rising to one in which they are falling. As the dollar appreciates relative to the peso, the peso value of the U.S. wage increases. If the exchange rate change is large enough, the U.S. wage in dollars might fall while its peso value rises.

The issue is in the specification of what motivates migrants. For example, if they are motivated by a desire to accumulate savings which they intend to repatriate, then migration will be sensitive to changes in the exchange rate. On the other hand, if workers care abut the differences in the amounts of non-traded goods they can consume within each country, then migration will be insensitive to changes in the exchange rate.

To eliminate the exchange rate effects on the migration decision, we fix the exchange rate in the migration equation at the base year level. Under bilateral trade liberalization, we find that urban unskilled migration from Mexico to the United States falls by half compared to scenario 3, in which the depreciating Mexican peso affects migration (table 8). In scenario 3, the decrease in the value of the peso makes dollar wages more attractive to potential migrants. Likewise, migration from rural Mexican to the rural labor market in the United States falls when the exchange rate does not affect the migration decision.

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[29]U.S. deficiency payments are modeled endogenously, with unit payments falling when producer prices rise. See Burfisher, Robinson, and Thierfelder (1992), Kilkenny (1991), and Kilkenny and Robinson (1990) for a discussion of how farm programs are modeled in the FTA-CGE model.

Table 7 — Sectoral Effects of an FTA on the U.S. and Mexico, with and without Migration, Percent Change from Base

	No migration		Internal migration		Internal and international migration	
	Output	Exports	Output	Exports	Output	Exports
United States						
Farm	0.2	44.5	0.2	47.9	0.4	51.3
Corn	4.9	128.4	5.2	134.9	6.7	141.8
Program crops	0.3	36.8	0.3	41.0	0.7	44.0
Fruit/vegetables	0.1	13.3	0.1	13.1	0.4	11.9
Other agric.	0.1	8.9	0.1	9.3	0.2	8.8
Food processing	-0.1	8.7	-0.1	9.0	0.1	8.5
Other light mfg.	0.0	7.4	0.0	7.6	0.1	7.1
Oil/gas	0.0	17.8	0.0	18.0	0.0	17.7
Intermediates	0.1	8.4	0.1	8.4	0.2	8.0
Consumer durables	0.0	9.5	0.0	9.5	0.2	9.3
Capital goods	0.1	9.5	0.1	9.5	0.1	9.2
Services	0.0	-2.4	0.0	-2.4	0.1	-2.6
Mexico						
Farm	0.1	10.2	-0.3	9.4	-1.1	8.8
Corn	-8.8	0.0	-10.8	0.0	-13.1	0.0
Program crops	-3.7	0.0	-4.5	0.0	-5.5	0.0
Fruit/vegetables	7.7	21.7	6.5	21.2	5.2	21.1
Other agric.	0.6	2.2	0.5	2.0	0.0	2.0
Food processing	0.1	7.7	0.0	7.6	-0.5	7.7
Other light mfg.	0.7	8.8	0.8	8.9	0.6	9.0
Oil/gas	0.0	4.3	0.0	4.3	0.0	4.5
Intermediates	1.5	4.0	1.6	4.1	1.4	4.2
Consumer durables	4.3	5.5	4.7	5.8	4.7	5.8
Capital goods	2.8	7.7	2.9	7.8	2.8	7.7
Services	-0.2	0.1	-0.1	0.2	-0.3	0.2

Notes: Real output and exports. Exports are to partner country (U.S. or Mexico).

When we eliminate the exchange rate effects, both rural and urban unskilled wages fall in Mexico under NAFTA. In Mexico's rural labor market, migration effects no longer dominate the effects of relative price changes in Mexico. Migration will, however, substantially mitigate the downward pressure on wages—the rural wage declines by 0.5% as opposed to 5.3% in the scenario with NAFTA and no migration.

The labor supply change in Mexico's urban unskilled labor market is more complex. There is a decline in the labor outflow to the U.S. urban unskilled labor market; 195,000 workers leave as opposed to 400,000 when exchange rates affect migration. While the workers entering from Mexico's rural labor market also declines (254,000 migrate from rural areas to the urban areas, as opposed to 340,000 migrants with exchange rate effects), the net result is an increase in the supply of urban unskilled labor. In contrast, there is a decrease in the labor supply when exchange rates are included in the migration decision. The increase in labor supply dominates the labor demand changes, and the urban unskilled wage declines by 0.5% in Mexico.

Migration effects still dominate in the United States, but have less of an impact on wages, reflecting the decline in the migration flows. Rural and urban unskilled wages each fall by 0.5% in the United States when there is no exchange rate effect, as opposed to a decline of 1.0% each with an exchange rate effect.

When modeling migration, we assume the wage differentials between the United States and Mexico are held constant at their base year levels. This treatment reflects a view that changes associated with NAFTA will not affect the wage differential in the migration equation; for example, we assume no changes in U.S. immigration restrictions. The results are certainly sensitive to this assumption. From equation 15, one can see that migration responds to changes in the wage differential parameter exactly the same as to changes in the exchange rate. For example, if Mexico grows more rapidly than the U.S., the model will generate a large decrease in migration in order to maintain the wage differential. Over the long run, with increased Mexican growth, one expects to observe growth in wages, a narrowing of the wage differential between the two countries, and a reduction in migration pressure. We have not sought to capture this mix of effects in the model because these long-run trends are not directly related to NAFTA, and the FTA-CGE model has been used primarily to explore the impact of NAFTA.

4.4 Implied Elasticities

In our analytical work, we identify three elasticities that affect the magnitude of migration. While we do not do sensitivity tests around the elasticities, we can define the values implicit in our data on the U.S. and Mexican economies.[30] The differences in elasticities help to explain the patterns of migration changes we observe in the empirical model.

The labor demand elasticities indicate the amount of migration needed to maintain fixed wage differentials across the linked labor markets (table 8). The more elastic the labor demand curve, the easier it is for the labor market to absorb labor without generating a large wage increase. For example, rural labor in Mexico can migrate either to the rural labor market in the United States or to the urban unskilled labor market in Mexico. The labor demand elasticity in Mexico's urban unskilled labor market is -1.83 while the labor demand elasticity in the U.S. urban unskilled labor market is -0.88. This difference in the labor demand elasticities helps to explain the "domino effect" we observe: rural workers in Mexico first go to the cities and then enter the U.S. urban unskilled labor market.

[30]These elasticities, however, are from a general equilibrium model, not a partial equilibrium model in which only one variable changes. The numbers we report are effectively the ratios of two total derivatives.

Table 8 — Implied Elasticities in the FTA-CGE Model

	United States	Mexico
Elasticity of labor demand with respect to the average wage:		
Rural labor	-0.88	-0.75
Urban unskilled labor	-1.87	-1.83
Output supply elasticity of corn with respect to output price	1.09	0.71
Elasticity of rural labor demand with respect to corn output	1.40	1.44

The output supply elasticity indicates the responsiveness of output to a relative price change. When output is very responsive to a relative price change, indicating curvature on the production possibilities frontier, there is potential for large migration flows. The output supply elasticity for corn, a sector which contracts under NAFTA, is 1.09. This slightly elastic supply curve and the dramatic price shock under NAFTA contribute to the large migration of workers out of Mexico's rural labor markets.

When output changes in response to a relative price change, the demand for labor also changes. For example, as the labor intensive good expands, the labor demand curve shifts to the right. If the labor demand curve is very responsive to output changes, one anticipates high levels of migration as there is initially pressure for wages to increase in that country. Focusing on corn, an important source of migration, we find that the elasticity of labor demand with respect to output is 1.44 in Mexico.

4.5 Stolper–Samuelson Effects in the 11-Sector Model

Our empirical results suggest that migration effects dominate the wage effects in equation (11) from the analytical model. However, one problem could be that a model of trade between the United States and Mexico violates the assumptions needed to develop the links between output prices and factor prices described in the Stolper–Samuelson theorem. The empirical model then becomes a poor test of the wage changes described in the analytical model. To better replicate the analytical model, we eliminate some of the distortions in the empirical model. We remove price distortions such as tariffs and quotas and remove sectoral differences in indirect and value added taxes. To minimize the impact of the Armington assumption, we increase the export transformation and import substitution elasticities. Other distortions that violate the assumptions of the Stolper–Samuelson theorem remain, including technology differences.

We introduce a relative price change in this stylized model by adding a 25% tariff on Mexican global corn imports, which raises Mexico's rural wage (table 9). Since corn is relatively labor intensive, this link between output prices and factor prices is consistent with the Stolper–Samuelson theorem. In the U.S., conversely, corn output declines and rural

Table 9 — Stolper-Samuelson Effects of Tariffs, with and without Migration, Percent Change from Base

	Mexican 25% tariff on corn	U.S. 50% tariff on fruits and vegetables	U.S. tariff with migration
Mexico	--- Percent change from base ---		
Corn output	8.8	0.6	0.1
Fruit and vegetable output	-0.1	-16.8	-17.0
Corn imports	-85.2	-2.4	-0.5
Rural wage	2.3	-1.4	0.0
United States			
Corn output	-6.8	-0.3	0.0
Fruit/vegetable output	0.2	1.0	1.1
Fruit/vegetable imports	-1.2	-90.6	-90.1
Rural wage	-0.7	0.4	-0.1
	--- 1,000 persons ---		
Mexican-U.S. rural migration	0	0	4
Mexican-U.S. unskilled migration	0	0	47
Mexican rural-urban migration	0	0	54

Notes: Real output and exports. Trade is to partner country (U.S. or Mexico).

wages fall.

A 50% tariff on U.S. global fruit and vegetable imports demonstrates a similar result: U.S. fruit and vegetable output rises, imports fall, and the U.S. rural wage rises. In Mexico, fruit and vegetable output falls dramatically, reflecting that Mexican exports to the U.S. accounts for a large share of Mexican production, and Mexican rural wages decline.

We next introduce migration into the scenario of a 50% tariff on U.S. fruit and vegetable imports. Because labor can now migrate out of Mexican agriculture, Mexican rural wages no longer fall when the U.S. imposes a tariff. In this scenario, 58,000 Mexican farm workers (about 1% of total farm labor) migrate out of Mexican agriculture, and 4,000 migrate to the U.S. For the U.S., we find that the effects of even a small labor migration flow dominate the Stolper-Samuelson effects of relative price changes. U.S. rural wages now decline with the introduction of a U.S. tariff.

In both countries, imports drop sharply following the imposition of a tariff, reflecting our assumption of very high elasticities of import substitution and export transformation in the distortion-free, non-Armington base. The result is much greater specialization than we would observe in the FTA-CGE model. This treatment biases the model in favor of Stolper–Samuelson effects, and should be viewed as an outer-bound estimate of the response of trade to changes in relative prices. Yet, even with the dramatic (and empirically unlikely) changes in trade observed in the stylized model, the Stolper–Samuelson links to wages are found to be small, and migration flows are enough to reverse the price effects. An important policy implication is that, in the presence of migration, the U.S. adoption of a tariff can hurt both countries.

5. Conclusion

Much of the debate over potential wage changes arising from the creation of NAFTA reflects views about the links between output prices and factor prices as described in the Stolper–Samuelson theorem. The model underlying the theorem assumes no international factor mobility, which is obviously unrealistic for the U.S. and Mexico, where there is significant labor migration. We develop an analytic trade model that includes both relative-price and migration effects, and show that the two effects on wages work in opposite directions. Furthermore, migration effects can more than fully offset relative-price effects. When one accounts for migration, any assessment of the net change in wages arising from changes in trade policy becomes an empirical question.

To analyze the empirical importance of the two mechanisms, we use an 11-sector FTA-CGE model of the United States and Mexico, in which the two countries are linked by trade and migration flows. We find that Stolper–Samuelson effects occur, but that they are very small, and have perhaps been given too much emphasis in the debate over the wage effects of NAFTA. Furthermore, migration effects largely dominate indirect price effects, generating wage changes under NAFTA that are contrary to expectations based on the Stolper–Samuelson theorem alone. For example, with no migration, removing protection causes rural wages in Mexico to fall (and rural wages in the U.S. to rise), reflecting Mexico's current high levels of protection to agricultural sectors. These results are consistent with the Stolper–Samuelson theorem. When we allow migration, however, the wage effects are reversed. The decline in the rural labor supply in Mexico causes the rural wage to rise rather than fall. Conversely, in the U.S, the rural wage falls, due to the increased rural labor migration from Mexico.

The analysis is more complex in the urban unskilled labor markets, where Mexican workers migrate both from rural areas to urban areas in Mexico, and from urban areas in Mexico to urban areas in the United States. In this case, we find that including migration reinforces the relative-price effects of NAFTA on urban unskilled wages. In Mexico, there is a net decline in supply of, as well as an increase in demand for, urban unskilled labors; both effects create pressure for the Mexican urban unskilled wage to rise. On the U.S. side, increased migration under NAFTA leads to small wage declines for both rural and urban unskilled workers.

Because of the importance of migration in determining the wage effects of NAFTA, we explore the sensitivity of our empirical model to the specification of migration. The amount of migration is sensitive to the treatment of the exchange rate in the migration equation. If workers in Mexico make wage comparisons in a common currency (say, because they are at least partly motivated by a desire to remit income), then the amount of migration is sensitive to changes in the exchange rate. Under NAFTA, the model projects a real depreciation of the Mexican Peso, which causes larger migration flows than would occur in a model in which migration is insensitive to changes in the exchange rate.

Finally, migration is very sensitive to the wage differential between the two countries. Given that Stolper-Samuelson effects are empirically very small, and given that technology is vastly different between the two countries, one would not expect to see any significant downward pressure on U.S. wages arising from changes in commodity trade and relative prices. Increased Mexican growth, however, would raise Mexican wages and lead to a significant decline in migration pressure. Our results support the view that both countries gain from NAFTA if it succeeds in its primary goal of increasing Mexican growth.

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