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THE RESPONSE OF LOCAL MAIZE PRICES TO THE 1983 CURRENCY DEVALUATION IN GHANA

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TABLE OF CONTENTS

ABSTRACT

This paper investigates the respective roles of spatial integration and arbitrage costs in explaining the adjustment of local prices to policy changes using the example of Ghana. We introduce a model of price formation and market integration that incorporates the price transmission process between local and central markets and also captures the implications for volatility of local prices. We explore the implications of the model for the time-path of price adjustments, as determined directly and indirectly through the marketing sector. We show that the price-adjustment process in a local market is determined by the degree of interdependence between that market and the central market in which a price-shock originates, and estimate the intertemporal and interspatial dynamics of the price adjustment process. Using data from wholesale maize markets in Ghana we find that reductions in local prices and local price variance following the introduction of economic reforms in 1983 can be traced to both local and central market forces, but that differences in the degree of market integration have important implications for long-run changes in arbitrage costs and the evolution of prices in outlying markets.

1. Introduction

A fundamental question that remains unanswered in most countries undergoing economic reform is to what extent local markets respond to structural and macroeconomic policy changes. The objective of this paper is to explore this question theoretically and empirically, and to assess the respective roles of spatial integration and arbitrage costs in explaining price changes following from economic reforms in Ghana. In doing this, we seek to address issues of both major policy concern and continuing academic interest. For example, considerable attention has been focused on the relative isolation of rural markets and the implications of this isolation for agricultural producers and consumers (e.g. de Janvry, Fafchamps, and Sadoulet 1991; Fafchamps 1992; Saha and Stroud 1994). Nevertheless, few attempts have formally linked price changes in rural markets to specific policy events. The present study seeks to fill this gap by building upon a model of price formation and market integration. We introduce a dynamic model of price formation that measures spatial integration and arbitrage costs and use it to gauge the response of local agricultural prices to policy changes in Ghana. Our efforts are motivated first by concerns that price changes are poorly transmitted between central and regional markets in rural Africa, and second by a recognition that the ways in which agricultural producers and consumers react to changes in sectoral, trade, and macroeconomic policies depends upon the extent to which local market prices respond to changes in central market prices.

We first examine price formation analytically. In section 2 we introduce a model of wholesale price formation and market integration that incorporates the price transmission process between local and central markets and also captures the implications of this process for volatility of local prices. We argue that the link between prices and stockholding behavior provides a mechanism for both intertemporal and spatial arbitrage, and therefore that central market price history can explain price levels and price variability in outlying markets. In section 3 we explore the implications of the model for the time-path of price adjustments, as determined directly and indirectly through the marketing sector. We show that the price adjustment process in a market is determined by the degree of interdependence between that market and the central market in which a price-shock originates, and we outline a procedure for measuring the speed and magnitude of this impact. We also demonstrate that a change in the degree of market connectedness affects prices both contemporaneously and dynamically through impacts on arbitrage costs. Finally, in section 4 we examine wholesale prices in three important maize markets in Ghana, and empirically estimate the intertemporal and interspatial dynamics of the price adjustment process. In doing this we place particular attention on the role of policy changes in explaining the observed decline in local prices after the introduction of economic reforms in 1983, as well as the time path of this price decline. We find that reductions in local price levels and price variance that followed inception of economic reforms in 1983 can be traced to both local and central market forces, but that differences in the degree of market integration had important implications for long-run changes in arbitrage costs and the evolution of prices in outlying markets. The paper ends with conclusions and prospects for future research.

2. Price formation, market integration, and local price volatility

2.1 A model of price formation

Our investigation of wholesale maize price formation begins with a static model of price formation. We posit a local market, the price in which is determined by the price in the central, reference market. We denote the local and central markets by the superscripts *L* and *C*, respectively. The price in the local market can be written as:

$$(1) \qquad P_t^L = \alpha_0^L + \alpha_1^L \, time + \beta^L P_t^C + \mu_t^L.$$

With price measured in levels, the intercept in equation (1) denotes fixed costs of marketing and the coefficient on the central market price measures a proportional markup, i.e. an arbitrage cost, from the central to local market.[1]

[1] Cointegration tests examen whether the prices in equation (1) move together, that is, whether the differential represented by μ is stationary. These tests are explored

Although equation (1) is instructive, it is incomplete. In order to investigate the speed with which new price information is incorporated into future prices one requires a more fully specified dynamic model. Despite some recent criticisms of Ravallion's (1986) model (e.g. Alexander and Wyeth 1994; Dercon 1995), we find no evidence to reject an assumption of weak exogeneity in the current study, and follow Ravallion's approach here. Using j to indicate lags, and using X to denote a matrix that includes an intercept, a time trend, seasonal dummies, and other variables, expansion of equation (1) yields:

$$(2) \qquad P_t^L = \sum_{j=1}^{n} \alpha_j P_{t-j}^L + \sum_{j=0}^{n} \beta_j P_{t-j}^C + \gamma X_t + \varepsilon_t \ .$$

Interpretation of equation (2) is as follows. If $\beta_j = 0 \ \forall j$ then the local market is segmented from the central market. In contrast, if $\beta_0 = 1$ then price changes are immediately transmitted from the central market to the local market. Furthermore, if the central and regional markets are integrated in the long run, then $\Sigma\alpha + \Sigma\beta = 1$, and the number of lags required to ensure this equality provides evidence of integration that is less immediate than instantaneous price transmittal. Standard F- and t-tests applied to estimated

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empirically in section 4.

coefficients of equation (2) can be used to investigate hypotheses regarding short-run or long-run integration.[2]

2.2 Modeling local price volatility

To link market integration to local price volatility, the dynamic price equation must be modified further. To do this we rely upon the reasoning of the price formation model presented by Deaton and Laroque (1992). Their model shows that the link between prices and stockholding behavior creates a link between current-period price volatility and past prices. Price in any period will depend on the domestic harvest as well as past inventories and carryover stocks. The equilibrium price function will be decreasing with first-order stochastic increases in supply shock distributions. In addition, when there is no current period addition to inventories, the current price will be determined solely by the harvest level and past inventories. Autocorrelation

[2] In long-run equilibrium equation (2) can be manipulated to obtain:

$$P_t^L = (1 + b_1)\, P_{t-1}^i + b_2\, (P_t^C - P_{t-1}^C) + (b_3 - b_1)\, P_{t-1}^C + \gamma^L X_t^L + \varepsilon_t^L$$

where $b_1 = \alpha_1 - 1$; $b_2 = \beta_0$; and $b_3 = \alpha_1 + \beta_0 + \beta_1 - 1$. In long run equilibrium $(1 + b_1)$ and $(b_3 - b_1)$ will be the respective contributions of local and central market price histories to current prices. In a well-integrated market, the latter will have a comparatively strong influence on the local price level. Timmer (1987) defines the ratio $(1 + b_1)/(b_3 - b_1)$ as an index of market connectedness (IMC) and suggests that values less than 1 indicate short-run market integration. Timmer also argues that b_2 can be used as an indicator of short-run price transmittal. The coefficient measures the degree to which any price change in the reference market is transmitted to the local market.

in prices, therefore, is evidence of commodity storage. In the likely scenario of positive storage and some degree of market connectedness, the current-period price in a local market will depend on previous prices in that market, central market prices, and harvests.[3]

A link to price variance is less transparent, but can be easily reasoned. Denote one-step ahead price variance conditional on current price as $V(p_{t+1}|p_t)$. Deaton and Laroque show that a higher current-period price produces greater price volatility in the next period, that is, $\partial V(p_{t+1}|p_t)/\partial p_t \geq 0$. The reason for this is that a high price induces inventory holders to sell, and lower inventories lead to greater price variance in the future. For example, a combination of bad harvests and low inventories can produce sharp price increases. Conversely, low prices encourage stockholders to keep or increase inventories, which thereby dampen subsequent price rises. Testing whether local price variance is influenced by past central-market prices requires that one regress a measure of local price variance on central market price history.

One final proposition follows from the observation that domestic consumers and inventory holders compete for grain, and that central-market price changes influence local-market price volatility. Since higher production reduces prices and increases inventories, higher production should lead to

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[3] This presentation assumes no external trade of the commodity. For an application that accounts for possible trade, see Shively (1996).

smaller price rises; that is, the correlation between domestic harvest levels and price variance will be negative. Although a closed-form solution for the equilibrium price function cannot be easily derived, reduced-form equations describing the conditional mean and conditional variance can be posited. Conjectures regarding price variance can be tested by simultaneously estimating equations for price levels and price variance. One way to do this is to estimate the parameters of an autoregressive conditionally heteroskedastic regression (ARCH) model (Engle 1982; Bollerslev, Chou, and Kroner 1992). The ARCH model posits an error structure in which the size (but not the sign) of the residual is predictable. Unconditional variance in the model is assumed to be homoskedastic, but variance at time *t*, conditional on prior period information is heteroskedastic. An ARCH model applied in the current context is described by the following equations:

$$\textbf{(3)} \qquad P_t^L = \sum_{j=1}^{n} \alpha_j \, P_{t-j}^L + \sum_{j=0}^{n} \beta_j \, P_{t-j}^C + \gamma X_t + \varepsilon_t$$

$$\textbf{(4)} \qquad (\varepsilon_t)^2 + \sum_{k=1}^{q} [\delta_k \, \varepsilon_{t-k}^2 + \varphi_k^L \, P_{t-k}^L + \varphi_k^C \, P_{t-k}^C] + \lambda \, Z_t + v_t \quad .$$

Equation (3) describes the conditional mean of the price process for the local market over time, and is identical to equation (2). Equation (4) describes evolution of conditional price variance. Both local and central market prices appear as explanatory factors in equation (4). This allows one to measure the extent to which local price volatility depends on local and central market stocks. A positive coefficient for ϕ^L is consistent with a hypothesis that local-market storage reduces local price volatility. Similarly, a positive coefficient for ϕ^C is consistent with a hypothesis that central-market storage reduces local-market price volatility. As before, the matrix $\boldsymbol{X}$ contains an intercept, seasonal dummies, a time trend, and a measure of production. Similarly, $\boldsymbol{Z}$ contains predetermined variables that are believed to influence or explain residual variance.

3. Adjustment, spatial integration, and the time-path of local prices

3.1 The dynamics of price adjustment

Given an initial shock to the central-market price, the dynamics of the adjustment process involve a series of interim multipliers as initial shocks fluctuate, converge, and stabilize. In the context of the model introduced above, the cumulative effect after *j* periods of a central-market price shock on the price in an outlying market can be computed as:

$$\textbf{(5)} \qquad \beta_j^{C,L} = \sum_{h=0}^{j} \frac{\partial E[P_{t+h}^{L}]}{\partial P_t^{C}} \quad .$$

Complete adjustment of the process is given by the long-run dynamic multiplier:

$$\beta^{C,L} = \lim_{j \to \infty} \beta_j^{C,L} \quad . \qquad (6)$$

The *speed* of price transmission can be calculated by computing the time T that it takes for the intermediate multipliers to convergence to within a certain range of the long-run multiplier. The convergence rule is to find T such that $|\beta_T / \beta - 1| < \epsilon$ and $|\beta_K / \beta - 1| < \epsilon$ for every $j > T$, where ϵ is a tolerance limit and β_K is the estimated multiplier after j periods.

The model of market integration can be linked to the process of local price formation. We do this in order to model the adjustment of local market prices to a policy change that initially affects the central market. As an illustration, figure 1 shows the process of price adjustment. In line with the observed changes in Ghana, the central price is shown here to decline following reform in period t_a (Alderman and Shively 1996). The model of spatial integration predicts that this price change will be transmitted to the local market between time t_a and time t_{a+1}, a period that may range from a few weeks to a few months.

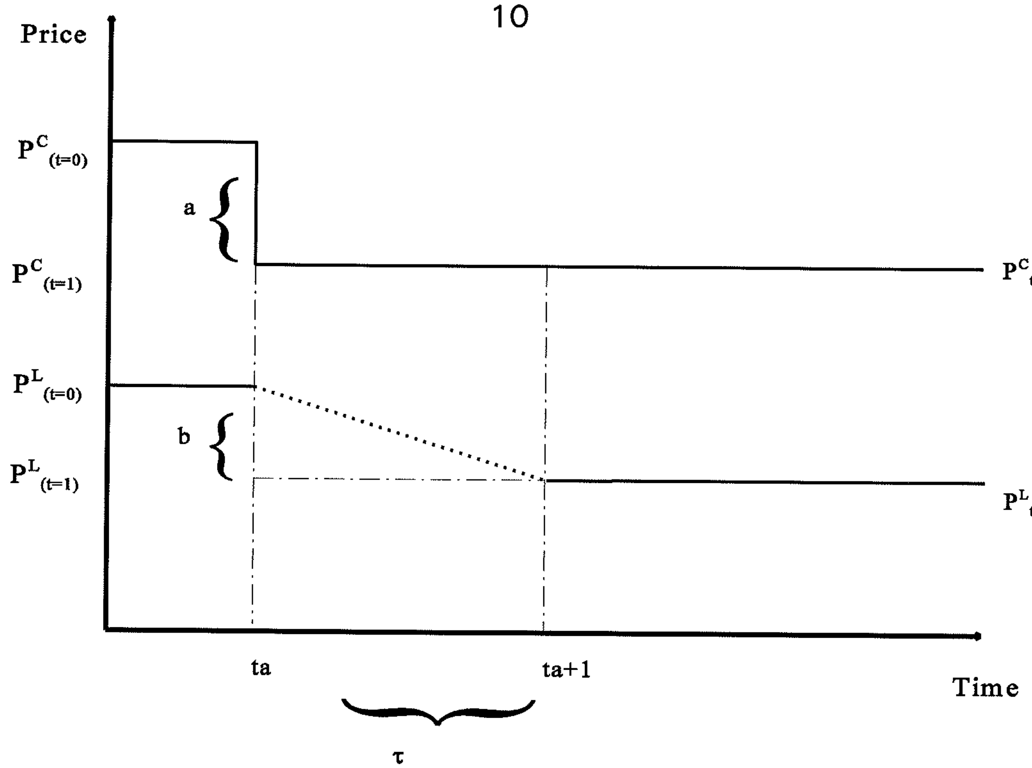

Fig. 1. Dynamics of local price adjustment
(a $= \Delta P^{C}_{ta}$; b $= \Delta P^{L}_{ta+1}$; τ = speed of transmission)

Derivation of the long-run multiplier assumes the existence of arbitrage between the central and local markets. The multiplier can therefore be understood as reflecting the process of price adjustment in the local and central markets to changing supply and demand conditions in these markets. These parameters should consequently bear some relationship to the local long run price formation process beyond the short run process captured by the spatial integration analysis. Moreover, because arbitrage costs play a key role in both the speed of adjustment and the actual degree of market connectedness, changes in arbitrage costs can be expected to lead to different patterns of price response for different local-market/central-market pairings.

Accordingly, the model of local price formation derived below is based on the following reasoning. If β_j^{CL} is the estimated value of the long run multiplier between the central market and a given local market after *j* periods, then the time path of prices in the local market can be expressed as $P_t^L\,(\beta_j^{CL}, \Delta T^L, P_{ta}^L, P_{ta+1}^L)$, where ΔT^L stands for the change in costs of spatial arbitrage; P_{ta}^L is the pre-reform price level in the local market at time period t_a; and P^L_{ta+1} is the price level after the shock has fully reached the local market at time period t_{a+1} (see Fig. 1).

3.2 Spatial integration, local arbitrage, and local price adjustment

At any given point in time, the contemporaneous relationship between the local and central market prices, P^L and P^C, respectively, can be written as:

(7) $$P_t^L = P_t^C - T_t^L$$

or equivalently as:

(8) $$P_t^C = P_t^L + T_t^L \; .$$

Our goal is to derive an expression for local prices that uses both the central-market price and a measure of arbitrage. To proceed, recall that equation (5) defines the dynamic long-run equilibrium relationship between the price in a given local market and the price in the central market. It expresses the cumulative adjustment of the local price to changes in the central-market price in previous periods. Approximating derivatives by first differences, and defining as one period the *h* units of time required for the long run multiplier to converge to its long run value, equation (7) can be rewritten as:

$$\Delta P^{L}_{t+1} = \beta^{L} \, \Delta P^{C}_{t} \tag{9}$$

Writing out equation (9) and inserting the values for P^{C} from equation (8) yields:

$$P^{L}_{t+2} - P^{L}_{t+1} = (P^{C}_{t+1} - P^{C}_{t})\beta^{C,L} \tag{10}$$

or equivalently,

$$P^{L}_{t+2} = (P^{L}_{t+1} + T^{L}_{t+1})\beta^{C,L} - (P^{L}_{t} + T^{L}_{t})\beta^{C,L} + P^{L}_{t+1} \quad . \tag{11}$$

Rearranged slightly, equation (11) yields a second-order linear difference equation that can be solved to obtain local prices P^{L}_{t} as a function of the long run multiplier β^{L} and local marketing costs T^{L}, as given by:

(12) $$P^L_{t+2} = (1 + \beta)\, P^L_{t+1} - \beta\, P^L_t + \beta\, \Delta T^L$$

or

(13) $$\frac{1}{\beta} P^L_{t+2} - \frac{(1 + \beta)}{\beta} P^L_{t+1} + P^L_t = \Delta T^L \quad .$$

Equation (13) in turn can be solved for P^L (see Tu 1994, pp. 46-50). This provides the following expression for the time path of local prices:[4]

(14) $$P^L_t = \zeta_t\, P^L_{(t=0)} + \varrho_t\, P^L_{t=1)} + \varphi_t\, \Delta T^L$$

$$where \quad \zeta_t = \frac{\beta - \beta^t}{\beta - 1} \; ; \; \varrho_t = \frac{\beta^t - 1}{\beta - 1} \; ; \; and \quad \varphi_t = (\frac{\beta}{\beta - 1})t \quad .$$

Equation (14) express the local-market price at time t as a function of the initial (pre-reform) price, the long-run multiplier, and the change in arbitrage costs *ΔT*. It says that the price level at any time *t* depends on its value in the distant past, but also indicates that prices depend on how well markets are connected and on the cost of spatial arbitrage. In other words, changes in the degree of market integration or the cost of marketing not only affects local prices contemporaneously, but also affect the evolution of these prices over

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[4] See Badiane and Nuppenau (1996).

time.[5] The expression for the time path of local prices derived here exposes the relationships between spatial integration among local markets, the cost of local arbitrage, and the adjustment of local prices to shocks in leading markets.

3.3 Marketing and the transmission of price shocks

We turn now to an analysis of the role of the marketing system in transmitting the effects of policy reforms. We assume that a policy change first affects prices in the central market since these are more closely linked to production changes influenced by reform. The central market leads other markets in the price discovery process, and depending on the degree of integration between central and local markets, the effect of a policy change passes from the central market to outlying markets.

The first step in modeling the transmission process is to model the effect of reforms on the central-market price.[6] To do this, note from the previous section that $P^L_{(t=0)}$ in equation (14) can be computed as:

$$P^L_{(t=0)} = P^C_{(t=0)} - T_{(t=0)} \quad (15)$$

In contrast, $P^L_{(t=1)}$ is modeled to reflect the effect of changes in policies and their transmission to local markets *following* adjustments in the central

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[5] Differentiating equation (14) with respect to β gives the impact of improvements in the degree of market integration on the time path of local prices (see Badiane 1996,; pp. 14-15).

[6] Badiane (1996) and Badiane and Nuppenau (1996) discuss ways to model these effects.

market. For example, assume that a one-time shock in the central market is induced by a policy change, and that local markets have finished adjusting to this shock. Defining as one period the time it takes for the long-run multiplier to converge to its equilibrium value, the post-adjustment price in the local market is:

$$\text{(16)} \qquad P^L_{(t=1)} = \beta[(P^C_{(t=1)} - P_{(t=0)})^C] + P^L_{(t=0)} \quad .$$

Recall that $T_{(t=0)}$ is the cost of spatial arbitrage before the introduction of reforms, and that $P^C_{(t=0)}$ and $P^L_{(t=0)}$ are the pre-reform price levels observed in the central and local markets. Substituting these into equation (16) and using the identity given by equation (15) provides the values of $P^L_{(t=0)}$ and $P^L_{(t=1)}$ that are required to compute the local time path described by equation (14). Equation (14) thus allows us to estimate the time path of prices in the local market that follows a shock in the central market. In the next section we report empirical estimates of this time path.

4. Wholesale maize prices in Ghana and their determinants

4.1 Data sources and the measurement of variables

In this section we apply our model to maize markets in Ghana. Our focus is on maize given its widespread importance to Ghanaian producers and consumers: in 1988 maize constituted 55 percent of cereal demand in Ghana and 66 percent of cereal supply. We use monthly wholesale maize price data from three important maize markets: Bolgatanga, near the Burkina Faso border in Upper East; Makola, the southern, capital city market; and Techiman, in the maize growing region of Brong-Ahafo. Our source for data is the Ghana Ministry of Agriculture. These data, which are part of a larger data set containing wholesale and retail prices for major food items in 35 markets, constitute a set of uninterrupted monthly data from May 1980 through July 1993. Prices are expressed in Cedis per kilogram, and have been deflated by market-basket CPIs. The basic price series is augmented with annual statistics for maize production in Ghana as reported in the FAO production yearbook. In reporting results, the superscripts BO, MA, and TE are used to identify prices in Bolgatanga, Makola, and Techiman markets, respectively. In all cases, Techiman serves as the reference market.[7] Because relatively little maize is produced near Bolgatanga or Makola, we model the geographically distant markets of Bolgatanga and Makola as small country price takers for maize from Techiman.

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[7] Although foreign aid or irregular imports through Makola could have temporarily suspended or reversed market flows from Techiman to Makola, we find no statistical evidence for rejecting an hypothesis of weak exogeneity in these data. As an early reader of the paper pointed out, however, Bolgatanga prices occasionally fall below those of Techiman, which raises the possibility of reverse stock flows. Although reverse trade is unlikely, in order to reduce possible misinterpretation of results based on Techiman prices, we substitute for them an instrumented value based on prices from Sunyani, a market near Techiman, but farther removed from both Bolgatanga and Makola. Results based on analysis with these instrumented data do not differ markedly from those obtained using Techiman data directly.

4.2 Economic policy and policy reforms in Ghana

Historically, both direct and indirect government interventions depressed maize prices in Ghana while reducing price variability (Stryker 1991). Ghana's 1983 Economic Recovery Program (ERP) reduced or eliminated many interventions, but despite the earlier bias against the sector, evidence reported elsewhere suggests that these policy reforms were accompanied by a decline in real maize prices (Alderman and Shively 1996). In part this decline in prices may be linked to improvements in the transport sector and a decline in marketing costs that followed the introduction of reforms (Jebuni and Seini 1992; Stryker 1991). Although market prices have fallen in some cases, wholesale maize prices have remained fairly volatile, both seasonally and randomly.

Currency devaluation was a centerpiece of Ghana's structural adjustment program, and between April 1983 and October 1985, the Cedi fell from 2.75 per dollar to 60 per dollar. Successive devaluations and the adjustment of the real exchange rate, combined with trading and marketing reforms have tended to shift the sources of domestic maize supply away from imports to local output.

Figure 2 displays the sample time series of monthly wholesale maize prices for the three markets analyzed in this study. Coefficients of variation in these prices are typically 30-50 percent. Prices in Bolgatanga and Makola typically exceed those in Techiman by 20-30 percent. Although these margins remained roughly the same during 1983 a year in which Ghana and most of West Africa experienced drought regressions based on equation (1) suggest that marketing margins have been falling in the post-reform period: for each series an average time trend through the data is moderately, but significantly, negative (Figures 3 and 4).

Fig. 2. Wholesale maize prices in Ghana 1980-1993

Fig. 3. Wholesale price differential (Bolgatanga - Techiman) 1980-1993

Fig. 4. Wholesale price differential (Makola - Techiman) 1980-1993

4.3 Tests of cointegration and stationarity

Several pathways are available to test for cointegration of the local and central market price series. Here we employ the Phillips-Ouliaris-Hansen procedure outlined by Hamilton (1994), using regression residuals from market-specific regressions based on equation (1). That is, we first estimate equation (1) for the Bolgatanga and Makola markets, using as the reference market Techiman. The residuals from these regressions, u^{BO} and u^{MA}, are retained and then regressed on their own lagged values using a first-order autoregression. These AR(1) regressions results are reported in table 1. We subsequently conducted two tests of stationarity. The first is the Phillips-Ouliaris Z-test, which is based on the AR(1) residual regression with undifferenced data.. The second is the augmented Dickey-Fuller t-test, which is based on the AR(1) residual regression using data in first-differences. Tests are conducted at the 95 percent confidence level against a true specification with constant and trend. Both tests recommend rejection of the null hypothesis of no cointegration in favor of the alternative hypothesis of cointegrated series. This indicates that marketing margins are stationary. Note that these tests do not require non-zero trends in the data: although no statistically significant trend in margins emerges for Bolgatanga, the hypothesis of a negative time trend for margins cannot be rejected for Makola.

Table 1. Residual regressions for Bolgatanga and Makola

	Market	
Variable	Bolgatanga	Makola
Intercept	0.021 (2.083)	0.322 (0.904)
Time trend	-0.0004 (0.0177)	0.0020 (0.0007)
Lagged residual	0.367 (-.075)	0.581 (0.064)
Autocorrelation factor	0.364 (0.074)	-0.449 (0.071)
R^2	0.41	0.15
Number of observations	158	158

Note: standard errors are in parentheses.

Table 2. Cointegration tests using market price-difference regression residuals

Null Hypothesis: No cointegration		Market Price Difference	
Test	1% critical value	Bolgatanga-Techiman	Makola-Techiman
Phillips: Z_p	-28.90	-53.91	-146.16
Dickey-Fuller	-3.98	-5.78	-10.62
Test result		Reject null	Reject null

4.4 Cointegrating conditionally heteroskedastic price regressions

Regression results for dynamic price equations are presented in table 3. Columns 1 and 2 contain results for a homoskedastic version of the model described by equation (2). Inspection of partial autocorrelations from those regressions indicated that first-order autoregressive processes would be appropriate for the conditional mean equations for both the Bolgatanga and Makola regressions. To test for heteroskedasticity in the regressions, residuals from least-squares regression of equation (2) were retained and squared, and a Lagrange multiplier test was applied to nR^2_e, where n equals the number of observations in the sample, and the R^2 was obtained from least-squares regression of the squared residuals on a constant and lagged values of squared residuals. These ARCH test statistics have values of 10.6 and 11.7 for Bolgatanga and Makola, respectively, which in both cases exceed the χ^2 one-percent critical value of 6.63. The null hypothesis of homoskedastic variance is therefore rejected in favor of the alternative hypothesis of heteroskedasticity in both markets. The test indicates that ARCH estimation of the dynamic price equation is more efficient than OLS estimation. Columns 3 and 4 of table 3 contain results for ARCH model for the Bolgatanga and Makola regressions, respectively. These estimates are based on equations (3) and (4). Guided by diagnostic tests of residual autocorrelations, we estimate the conditional variance equation as a first-order process for both markets.

Table 3. Regression results for the dynamic price model

	AR(1)		ARCH	
	Bolgatanga	Makola	Bolgatanga	Makola
Constant	0.912	4.074	0.156	5.282
	(1.915)	(1.967)	(1.553)	(1.113)
1983 indicator	5.872	4.691	5.392	3.501
	(2.072)	(2.610)	(1.775)	(1.851)
Techiman (current)	0.284	0.604	0.273	0.625
	(0.064)	(0.071)	(0.055)	(0.042)
Techiman (t-1)	0.012	0.166	0.016	0.116
	(0.083)	(0.097)	(0.070)	(0.047)
Techiman (t-2)	0.249	-0.373	0.131	-0.275
	(0.081)	(0.096)	(0.064)	(0.045)
Techiman (t-3)	-0.025	0.387	-0.033	0.071
	(0.084)	(0.095)	(0.064)	(0.038)
Techiman (t-4)	-0.228	-0.190	-0.121	-0.043
	(0.075)	(0.092)	(0.057)	(0.028)
Local (t-1)	0.576	0.298	0.628	0.270
	(0.082)	(0.082)	(0.072)	(0.058)
Local (t-2)	0.060	0.158	0.083	0.240
	(0.096)	(0.082)	(0.078)	(0.057)
Local (t-3)	-0.026	0.097	-0.039	0.115
	(0.090)	(0.084)	(0.067)	(0.052)
Local (t-4)	0.003	-0.098	0.015	-0.105
	(0.069)	(0.076)	(0.056)	(0.042)
		Variance equation		
Constant	_	_	10.235	4.814
			(8.672)	(1.985)
Lagged residual	_	_	0.118	0.382
			(0.069)	(0.109)
Techiman (t-1)	_	_	-0.130	-0.534
			(0.207)	(0.149)
Local (t-1)	_	_	0.525	0.784
			(0.187)	(0.179)
Log-likelihood value	-464.7	-476.9	-439.9	-412.2
N	159	159	159	159

Note: Standard errors are in parentheses. Mean and variance regressions contained a production measure in addition to 11 monthly dummy variables corresponding to January-November.

To briefly summarize the results presented in columns 3 and 4 of table 3, recall that complete market segmentation implies that none of the Techiman prices significantly influences local market prices. This hypothesis is rejected for both Bolgatanga and Makola markets. A hypothesis of immediate integration with Techiman prices is also rejected for both markets. Tests of the restrictions necessary for long-run integration are not rejected at standard significance levels. An integration hypothesis, based on the criterion that $\Sigma\alpha + \Sigma\beta = 1$, cannot be rejected for models with 4-period lags in each market. On the grounds of brevity, models with different lag structures are not reported here. In most cases, the strength of the integration relationship improves as additional lags are added to the models, but the results do not change markedly beyond four lags. In short, these regression results support conjectures by Alderman (1993) and Asante, et al. (1989) that maize markets in Ghana are relatively well integrated.

4.5 Evidence regarding dynamic multipliers and the time path of local prices

The dynamic multipliers derived from the price equations reported in table 3 are presented in table 4. These indicate that for Bolgatanga, local-market price history is more important than central-market price history for price determination, but that the opposite holds for Makola. For both markets, the multipliers implied by the ARCH models place more weight on local price histories *vis-à-vis* central-market prices, and also imply somewhat larger multipliers overall. Model results are consistent with hypotheses of long-run integration. In the case of the four-period lag AR(1) model the sum of price parameters is 0.91 for Bolgatanga and 1.05 for Makola. For the ARCH model the corresponding values are slightly higher at 0.95 and 1.06. Timmer's Index of Market Connectedness (IMC) is 2.6 for Bolgatanga, and slightly less than 1 for Makola. These values underscore that the Bolgatanga market is relatively less integrated with the Techiman market than is the Makola market.

Table 4. Dynamic multipliers derived from price model

	AR(1)		ARCH	
	Bolgatanga	Makola	Bolgatanga	Makola
Central market	0.292	0.594	0.265	0.538
Local market	0.613	0.455	0.687	0.519

Values for the long-run dynamic multipliers that are implied by the ARCH results are 0.27 and 0.54 for Bolgatanga and Makola, respectively. These values are used to compute equation (14) to obtain the time paths of local prices in the two markets. Estimates of long-run multipliers reported in the literature for other markets typically range from 0.4 to 0.6. Thus the estimate for Bolgatanga is relatively low in comparison. The estimated time required to fully transmit a price shock, that is, the period from t_a to t_{a+1} is about four months in each market. This measure of the speed of adjustment is used to calculate average price and average arbitrage cost for construction of the price time path in the simulations presented below. Accordingly, $P^{L}_{(t=0)}$ and $P^{C}_{(t=0)}$ are the four-month averages of local (Bolgatanga and Makola) prices and central market (Techiman) prices at the time of reforms. We use the devaluation of April 1983 as our benchmark for the reform period. Thus, $P^{L}_{(t=0)}$ and $P^{C}_{(t=0)}$ represent the observed average prices in the third four-month period of 1983, with May 1983 to August 1993 corresponding to t_a. Based on the estimated speed of transmission of four months, the first four-month period of 1984 is used as t_{a+1}. The local price used for $P^{L}_{(t=1)}$, computed with the help of equation (16), also corresponds to that period.

The observed changes in spatial price spreads between Techiman, on the one hand, and Bolgatanga and Makola, on the other, are used as proxies for the changes in arbitrage costs, again using the same four-month time unit. Given that equation (13) was solved as a non-homogenous second-order difference equation, implying a constant ΔT, the average change in spatial price spreads between the individual four-month periods is used in the computations. During the period for which equation (14) is computed and which goes from the second four-month period of 1984 (II/84) to the second four-month period of 1993 (II/93), the average change in arbitrage cost between Techiman and Bolgatanga was -0.5 Cedis per four month-period. Between Techiman and Makola the corresponding figure was -0.4 Cedis.

Computed time paths of prices are presented in figures 5 and 6 for Bolgatanga and Makola, respectively. As explained previously, local price data enter into the computations for each market in the form of prevailing pre-reform price levels, $P^{L}_{(t=0)}$. These are calculated as the observed average price in t_a (III/1983). For Techiman, two initial values are entered. The first is the pre-reform price level, $P^{C}_{(t=0)}$, calculated as the average four-month price in III/83. The second is the price level immediately after the introduction of reforms, i.e $P^{C}_{(t=1)}$, for which the four-month price average in t_{a+1} (I/1984) is used.

The dotted line in figure 5 shows the evolution of observed prices in Bolgatanga. The solid line is the *ex post* prediction of these prices. These predictions are computed using equations (14) and (15), the pre-reform prices, the observed measure of spatial integration between Bolgatanga and Techiman (0.27), the observed decline in arbitrage costs between the two markets (-0.50), and Techiman prices observed immediately prior to and after the 1983 devaluation. The prediction indicates that the price decline in Techiman contributed to the fall in prices in Bolgatanga.[8] However, given the

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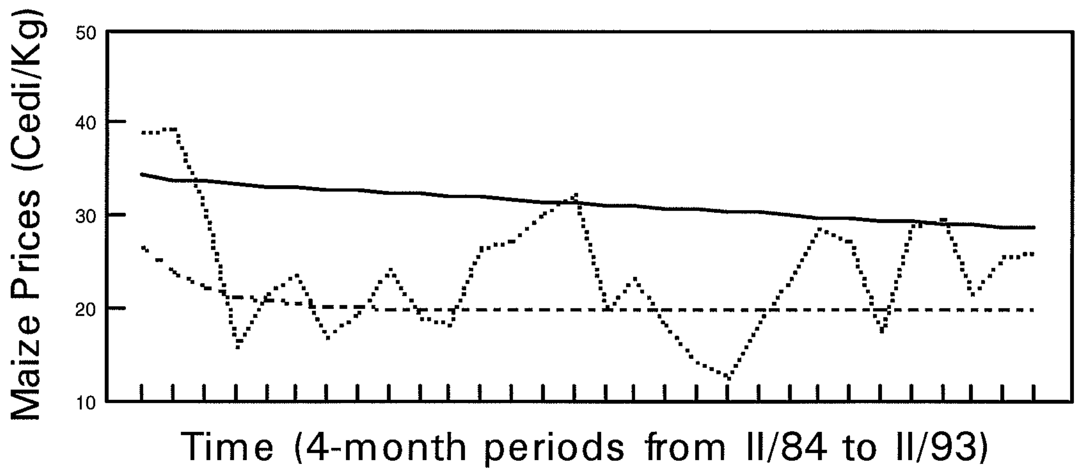
[8] Prices in Techiman fell from 53.17 to 40.54 Cedis between III/83 and I/84 while arbitrage costs between the two markets fell by an average of 0.5 Cedis every four-month period between III/84 and II/93.

relatively weak link between Techiman and Bolgatanga, the contribution of Techiman price changes to Bolgatanga price changes was small.

These results are in line with findings from the spatial integration model, which indicated that Bolgatanga prices are determined primarily by their own past values and local factors underlying them. In fact, based on the relatively low level of interconnectedness between Techiman and Bolgatanga one would expect that only a small amount of any price change in the former would be transmitted to the latter. To the extent that the weak connection between these markets is a reflection of a low level of arbitrage between them, one might also expect changes in arbitrage costs to have limited impact on the evolution of Bolgatanga prices.

To show the importance of market connectedness for the response of Bolgatanga prices to changes in Techiman prices and arbitrage costs, equation (14) is solved again, this time using a larger long-run multiplier value (0.60) and no change in arbitrage costs. This new predicted time path is represented by the dash-and-dotted line in figure 5. Comparing these two predicted time paths, one sees that poor market integration helps to explain the limited impact of a decline in Techiman prices and arbitrage costs on prices in Bolgatanga.



Notes:

1 Observed time path of local prices

2 Estimated time path based on actual average changes in arbitrage costs of $\Delta T = -0.5$ and the original value of $\beta = 0.27$

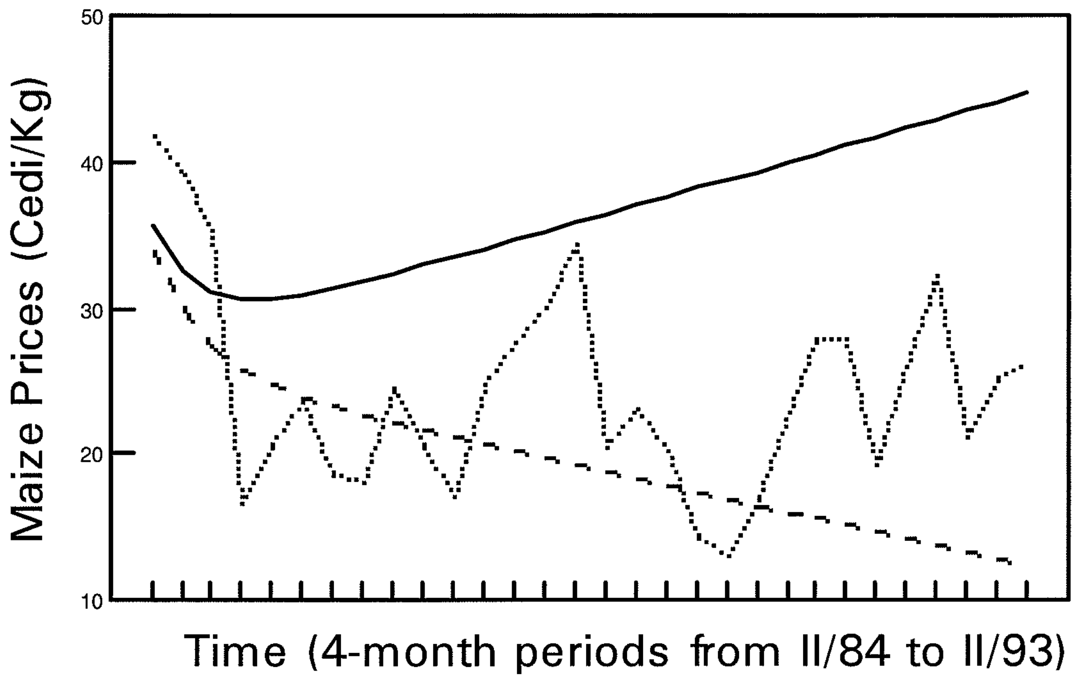
3 Estimated time path with no change in arbitrage costs ($\Delta T = 0$) and a value of $\beta = 0.6$

See tables A_1 and A_3, in appendix for computations.

Fig. 5. Marketing cost, integration, and local price adjustment in Bolgatanga

The importance of spatial integration for price transmission is confirmed by the results for the better connected Makola market (figure 6). Recall that the value of the long run multiplier for Makola is 0.54—double that for Bolgatanga. As a result, the predicted price change in Makola was much greater than in Bolgatanga, despite the fact that the observed reduction in arbitrage costs between Techiman and Makola (-0.40) was smaller than that observed between Techiman and Bolgatanga (-0.50). The solid line in figure 6 represents the predicted time path for Makola; the dotted line represents observed prices.

To gauge the sensitivity local prices changes to changes in the costs of arbitrage in Makola, equation (14) was again computed using the same long-run multiplier, but increasing arbitrage costs by an average of 0.5 Cedis per four-month period (compared with the observed average decline of -0.4 Cedis). The dash-and-dotted line in figure 6 shows the time path for this simulation. The increase in arbitrage costs has a large impact on the time path of local prices, despite the decline in Techiman prices. As one would expect, the increase in arbitrage costs dampens the impact of the fall in Techiman prices. In fact, prices in Makola not only decline less as a result of higher arbitrage costs, but they also begin to increase a year after the price reduction. This clearly illustrates that price and arbitrage cost changes in a central market can have unexpected and offsetting impacts when one accounts for the dynamic implications of arbitrage cost changes for long-run market integration.



Notes:

1 Observed time of local prices

2 Estimated time path based on actual average changes in arbitrage costs of $\Delta T = -0.4$ and the original value of $\beta = 0.54$

3 Estimated time path with average changes in arbitrage costs of $\Delta T = 0.5$ and the original value of $\beta = 0.54$

See tables A_2 and A_4 in appendix for computations.

Fig. 6. Marketing cost, integration, and local price adjustment in Makola

5. Conclusions and prospects for future work

We have shown that the price-adjustment process in a local market is determined by the degree of interdependence between that market and the central market in which a price-shock originates, as well as the intertemporal dynamics of the price-adjustment process as influenced by arbitrage costs. Our results were formalized analytically using a dynamic model of price formation and further analyzed with a simulation model.

We also showed that the price transmission process from central to outlying markets can influence price volatility. These results extend the early work of Ravallion (1985), as well as previous work on market integration by Alexander and Wyeth (1994); Dercon (1995); and Shively (1996). A key finding from this paper that should be considered in future market integration studies is the likelihood of heteroskedasticity in the error structure of dynamic price equations. We show that an ARCH model provides a convenient method for deriving more efficient estimates of the parameters of market integration model, as well as the long-run dynamic multipliers of price-adjustment models.

We explored empirically the implications of our model for the time-path of price adjustments, as determined directly and indirectly through the marketing sector. Using data from wholesale maize markets in Ghana we found that reductions in local prices and local price variance following the introduction of economic reforms in 1983 could be traced to both local and central market forces, but that differences in the degree of market integration between central and outlying markets had important implications for long-run changes in arbitrage costs and the evolution of prices in those outlying markets.

Our empirical analysis focused on three important markets in Ghana over the period 1980-1993. We found that the Techiman market--- in the maize growing region of Ghana---was well connected to the Makola market during the study period, in the sense central-market price history was more important for explaining price changes in Makola than was local-market price history. This finding is not surprising, given Makola's proximity to Techiman, and the fact that Makola is located in Accra and therefore exhibits a high intensity of trading activity. Market connectedness was less pronounced between Techiman and Bolgatanga, a market that lies at Ghana's northern border with Burkina Faso. In Bolgatanga, local-market price history was the predominant determinant of prices. Our findings indicated that wholesale maize prices fell in these markets following devaluation and inception of economic reforms, as did arbitrage costs between Techiman and the two outlying markets. In contrast, seasonality in prices remains high, with inter-year price volatility primarily driven by domestic production levels and local storage.

The results reported here need not imply an expanded direct role for the public sector in grain marketing in Ghana, since statistical evidence ndicates that grain prices are being transmitted across markets, and that the central markets serves an important role in buffering price changes in local markets. Nevertheless, the relative isolation of the Bolgatanga market---as evidenced by the relative importance of local market price histories in explaining local price levels and variability---suggests that improvements in local storage and transport systems would likely reduce food price variability in Bolgatanga and other relatively isolated markets. For example, results from the ARCH model indicate that a one-Cedi decline in the Techiman maize price led to a 0.5-Cedi reduction in price variance in the relatively well integrated Makola market, but only a 0.1-Cedi reduction in price variance in the relatively isolated Bolgatanga market.

The current model does not indicate the extent to which observed reductions in arbitrage costs translate into higher farm prices, nor the extent to which consumers have benefited from price changes. To gain greater insight into the welfare effects of the patterns described here, future work should attempt to supplement this analysis with microeconomic studies of household, farm, and trader behavior.

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TABLE A1. PRICE ADJUSTMENT IN BOLGATANGA: IMPACT OF ACTUAL CHANGES IN ARBITRAGE COSTS

t	P(a)	μ	Delta T	PI (t=0)	PI (t=1)	Pc (t=0)	Pc(t=1)	a	b	c	PI (t)
1	39.09	0.27	-0.50	39.09	35.68	53.17	40.54	-10.55	45.31	-0.37	34.39
2	39.34	0.27	-0.50	39.09	35.68	53.17	40.54	-13.40	47.91	-0.55	33.96
3	30.87	0.27	-0.50	39.09	35.68	53.17	40.54	-14.17	48.62	-0.74	33.70
4	16.32	0.27	-0.50	39.09	35.68	53.17	40.54	-14.38	48.81	-0.92	33.50
5	21.90	0.27	-0.50	39.09	35.68	53.17	40.54	-14.44	48.86	-1.11	33.31
6	23.71	0.27	-0.50	39.09	35.68	53.17	40.54	-14.45	48.87	-1.29	33.12
7	17.11	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-1.48	32.94
8	19.91	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-1.66	32.75
9	24.64	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-1.85	32.57
10	19.04	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-2.03	32.38
11	18.52	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-2.22	32.20
12	26.81	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-2.40	32.01
13	27.32	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-2.59	31.83
14	30.59	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-2.77	31.64
15	32.39	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-2.96	31.46
16	20.29	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-3.14	31.27
17	23.57	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-3.33	31.09
18	18.40	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-3.51	30.90
19	14.32	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-3.70	30.72
20	12.94	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-3.88	30.54
21	18.95	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-4.07	30.35
22	23.66	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-4.25	30.17
23	28.84	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-4.44	29.98
24	27.50	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-4.62	29.80
25	17.95	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-4.81	29.61
26	29.23	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-4.99	29.43
27	29.90	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-5.18	29.24
28	21.72	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-5.36	29.06
29	25.90	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-5.55	28.87
30	26.28	0.27	-0.50	39.09	35.68	53.17	40.54	-14.46	48.88	-5.73	28.69

Note: μ is longrun multiplier estimated from the co-integration model; Delta T is the average change in arbitrage costs.
a, b, and c refer to 1st term, 2nd term, and 3rd term, respectively on RHS of equation 38.

PI (t) is the estimated price level in period t and is equal to the sum of a, b, and c.

TABLE A2. PRICE ADJUSTMENT IN MAKOLA: IMPACT OF ACTUAL CHANGES IN ARBITRAGE COSTS

t	P(a)	μ	Delta T	Pl (t=0)	Pl (t=1)	Pc (t=0)	Pc(t=1)	a	b	c	Pl (t)
1	41.83	0.54	-0.40	41.27	34.45	53.17	40.54	-22.29	53.05	-0.91	29.83
2	39.17	0.54	-0.40	41.27	34.45	53.17	40.54	-34.32	63.10	-1.41	27.37
3	35.41	0.54	-0.40	41.27	34.45	53.17	40.54	-40.82	68.52	-1.88	25.83
4	16.81	0.54	-0.40	41.27	34.45	53.17	40.54	-44.33	71.45	-2.35	24.78
5	20.90	0.54	-0.40	41.27	34.45	53.17	40.54	-46.22	73.03	-2.82	23.99
6	23.63	0.54	-0.40	41.27	34.45	53.17	40.54	-47.25	73.89	-3.29	23.36
7	18.62	0.54	-0.40	41.27	34.45	53.17	40.54	-47.80	74.35	-3.76	22.79
8	18.19	0.54	-0.40	41.27	34.45	53.17	40.54	-48.10	74.60	-4.23	22.28
9	24.73	0.54	-0.40	41.27	34.45	53.17	40.54	-48.26	74.73	-4.70	21.78
10	20.57	0.54	-0.40	41.27	34.45	53.17	40.54	-48.35	74.81	-5.17	21.30
11	17.29	0.54	-0.40	41.27	34.45	53.17	40.54	-48.39	74.84	-5.63	20.82
12	24.75	0.54	-0.40	41.27	34.45	53.17	40.54	-48.42	74.87	-6.10	20.34
13	27.69	0.54	-0.40	41.27	34.45	53.17	40.54	-48.43	74.88	-6.57	19.87
14	30.01	0.54	-0.40	41.27	34.45	53.17	40.54	-48.44	74.88	-7.04	19.40
15	34.48	0.54	-0.40	41.27	34.45	53.17	40.54	-48.44	74.89	-7.51	18.93
16	20.52	0.54	-0.40	41.27	34.45	53.17	40.54	-48.44	74.89	-7.98	18.46
17	23.28	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-8.45	17.99
18	20.34	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-8.92	17.52
19	14.29	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-9.39	17.05
20	13.22	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-9.86	16.58
21	17.23	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-10.33	16.11
22	22.84	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-10.80	15.64
23	27.95	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-11.27	15.17
24	28.06	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-11.74	14.70
25	19.44	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-12.21	14.23
26	26.13	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-12.68	13.77
27	32.33	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-13.15	13.30
28	21.22	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-13.62	12.83
29	25.23	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-14.09	12.36
30	26.37	0.54	-0.40	41.27	34.45	53.17	40.54	-48.45	74.89	-14.56	11.89

Note: μ is longrun multiplier estimated from the co-integration model; Delta T is the average change in arbitrage costs.
a, b, and c refer to 1st term, 2nd term, and 3rd term, respectively on RHS of equation 38.

PI (t) is the estimated price level in period t and is equal to the sum of a, b, and c.

TABLE A3. PRICE ADJUSTMENT IN BOLGATANGA: NO CHANGES IN ARBITRAGE COSTS AND INCREASE IN LEVEL OF INTEGRATION FROM 0.3 TO 0.6

t	P(a)	μ	Delta T	Pl (t=0)	Pl (t=1)	Pc (t=0)	Pc(t=1)	a	b	c	Pl (t)
1	39.09	0.60	0.00	39.09	31.51	53.17	40.54	-23.45	50.42	0.00	26.97
2	39.34	0.60	0.00	39.09	31.51	53.17	40.54	-37.53	61.76	0.00	24.24
3	30.87	0.60	0.00	39.09	31.51	53.17	40.54	-45.97	68.57	0.00	22.60
4	16.32	0.60	0.00	39.09	31.51	53.17	40.54	-51.04	72.65	0.00	21.62
5	21.90	0.60	0.00	39.09	31.51	53.17	40.54	-54.08	75.10	0.00	21.03
6	23.71	0.60	0.00	39.09	31.51	53.17	40.54	-55.90	76.57	0.00	20.68
7	17.11	0.60	0.00	39.09	31.51	53.17	40.54	-56.99	77.46	0.00	20.46
8	19.91	0.60	0.00	39.09	31.51	53.17	40.54	-57.65	77.99	0.00	20.34
9	24.64	0.60	0.00	39.09	31.51	53.17	40.54	-58.04	78.30	0.00	20.26
10	19.04	0.60	0.00	39.09	31.51	53.17	40.54	-58.28	78.49	0.00	20.21
11	18.52	0.60	0.00	39.09	31.51	53.17	40.54	-58.42	78.61	0.00	20.19
12	26.81	0.60	0.00	39.09	31.51	53.17	40.54	-58.51	78.68	0.00	20.17
13	27.32	0.60	0.00	39.09	31.51	53.17	40.54	-58.56	78.72	0.00	20.16
14	30.59	0.60	0.00	39.09	31.51	53.17	40.54	-58.59	78.74	0.00	20.15
15	32.39	0.60	0.00	39.09	31.51	53.17	40.54	-58.61	78.76	0.00	20.15
16	20.29	0.60	0.00	39.09	31.51	53.17	40.54	-58.62	78.77	0.00	20.15
17	23.57	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.77	0.00	20.15
18	18.40	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
19	14.32	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
20	12.94	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
21	18.95	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
22	23.66	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
23	28.84	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
24	27.50	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
25	17.95	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
26	29.23	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
27	29.90	0.60	0.00	39.09	31.51	53.17	40.54	-58.63	78.78	0.00	20.15
28	21.72	0.60	0.00	39.09	31.51	53.17	40.54	-58.64	78.78	0.00	20.15
29	25.90	0.60	0.00	39.09	31.51	53.17	40.54	-58.64	78.78	0.00	20.15
30	26.28	0.60	0.00	39.09	31.51	53.17	40.54	-58.64	78.78	0.00	20.15

Note: μ is longrun multiplier estimated from the co-integration model; Delta T is the average change in arbitrage costs.

a, b, and c refer to 1st term, 2nd term, and 3rd term, respectively on RHS of equation 38.
PI (t) is the estimated price level in period t and is equal to the sum of a, b, and c.

TABLE A4. PRICE ADJUSTMENT IN MAKOLA: 0.5 AVERAGE INCREASE IN OBSERVED ARBITRAGE COSTS PER PERIOD

t	P(a)	µ	Delta T	Pl (t=0)	Pl (t=1)	Pc (t=0)	Pc(t=1)	a	b	c	Pl (t)
1	41.83	0.54	0.50	41.83	35.01	53.17	40.54	-22.59	53.92	1.17	32.50
2	39.17	0.54	0.50	41.83	35.01	53.17	40.54	-34.79	64.12	1.76	31.10
3	35.41	0.54	0.50	41.83	35.01	53.17	40.54	-41.37	69.64	2.35	30.61
4	16.81	0.54	0.50	41.83	35.01	53.17	40.54	-44.93	72.61	2.93	30.62
5	20.90	0.54	0.50	41.83	35.01	53.17	40.54	-46.85	74.22	3.52	30.89
6	23.63	0.54	0.50	41.83	35.01	53.17	40.54	-47.89	75.09	4.11	31.31
7	18.62	0.54	0.50	41.83	35.01	53.17	40.54	-48.45	75.56	4.70	31.81
8	18.19	0.54	0.50	41.83	35.01	53.17	40.54	-48.75	75.81	5.28	32.34
9	24.73	0.54	0.50	41.83	35.01	53.17	40.54	-48.91	75.95	5.87	32.90
10	20.57	0.54	0.50	41.83	35.01	53.17	40.54	-49.00	76.02	6.46	33.48
11	17.29	0.54	0.50	41.83	35.01	53.17	40.54	-49.05	76.06	7.04	34.06
12	24.75	0.54	0.50	41.83	35.01	53.17	40.54	-49.07	76.08	7.63	34.64
13	27.69	0.54	0.50	41.83	35.01	53.17	40.54	-49.09	76.09	8.22	35.22
14	30.01	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.10	8.80	35.81
15	34.48	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.10	9.39	36.40
16	20.52	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	9.98	36.98
17	23.28	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	10.57	37.57
18	20.34	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	11.15	38.16
19	14.29	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	11.74	38.74
20	13.22	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	12.33	39.33
21	17.23	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	12.91	39.92
22	22.84	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	13.50	40.50
23	27.95	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	14.09	41.09
24	28.06	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	14.67	41.68
25	19.44	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	15.26	42.26
26	26.13	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	15.85	42.85
27	32.33	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	16.43	43.44
28	21.22	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	17.02	44.03
29	25.23	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	17.61	44.61
30	26.37	0.54	0.50	41.83	35.01	53.17	40.54	-49.10	76.11	18.20	45.20

Note: µ is longrun multiplier estimated from the co-integration model; Delta T is the average change in arbitrage costs.
a, b, and c refer to 1st term, 2nd term, and 3rd term, respectively on RHS of equation 38.

PI (t) is the estimated price level in period t and is equal to the sum of a, b, and c.