Adapting Johansen's Estimation Method for Flexible Regime-dependent Cointegration Modelling

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Introduction

Empirical research in price transmission analysis examines the underlying factors driving horizontal, that is, markets of one commodity in space, or vertical price dynamics, that is, along the processing chain, in food markets. Considerable evidence was obtained in recent years that parameters governing price interdependencies might not be stable. Nonconstant parameters which take regime-dependent values quantifying the speed of price transmission for each regime, that is, for a number of recurring economic states of a market, appeared to be an adequate modelling alternative. If these characteristics are disregarded, the resulting (global) estimates are weighted averages of the (hidden) regime-dependent parameters. Regime-dependent approaches are both from a practical and an econometric perspective preferable since the model would be otherwise oversimplifying or misspecified, i.e., parameter estimates would not reflect major features of the market.

For example, the literature on asymmetric price transmission (APT) suggests that asymmetries might play a crucial role in price formation processes (see, e.g., Meyer and von Cramon-Taubadel, 2004). Such APT models are a special type of threshold cointegration models for which the threshold is exogenously set by the researcher, that is, the threshold is set to zero since the sign of the error-correction term (the threshold variable) is used to delineate between regimes (Ihle, 2010). Although typically used in the context of vertical price transmission, they are also useful tools for the analysis of price dynamics across space. For example, Abdulai (2000) or Meyer and von Cramon-Taubadel (2004) study the implications of market power on asymmetries in the vertical transmission of price signals between markets. On the other hand, Jensen (2007, 2009) shed light on the importance of information flow on price formation and price dynamics. Stephens et al. (2008) highlight the role of seasonalities.

We generalize the APT model suggest by von Cramon-Taubadel (1998) to a multivariate setting in order to be able to regard more than two price series, more than one cointegration relationship and more than one category classifying the observations into regimes. The suggested model not only generalizes the traditional APT model which models pairs of prices with one cointegration relationship but offers a general framework for the estimation of multivariate regime-dependent models which are apt to assess an arbitrary number of regimes. This multivariate model is capable of accommodating a wide range of regime types or a combination of two or more of regime categories that are of interest in price transmission analysis in order to obtain sophisticated regime-dependent estimates. The regimes are to be exogenously determined by the researcher. Examples include seasonalities in production or demand or asymmetries in price transmission (it may hence be seen as a generalized APT model), that is, regimes defined according to the sign of the deviations from equilibrium.

A number of estimation strategies and model types have been proposed in the literature (Frey and Manera, 2007). Regime-switching models with a known classification rule for the assignment of the regimes are estimated so far either with the Engle-Granger or the Stock-Watson methodology (Frey and Manera, 2007). We, however, propose an adaption of the Johansen method (Johansen, 1988, 1991) for the estimation of such general regime-dependent models since it was shown to have statistical properties which are superior to the remaining approaches for most settings (Gonzalo, 1994) and explain in detail how the approach can be be changed for the given purpose.

To illustrate our proposed model and estimation method we employ a unique dataset of prices on five tomato markets in Ghana, observed bi-weekly over a period of three years, using an APT model, which is perhaps the most common exogenous regime-dependent model used in the empirical price transmission literature, with seasonal regimes for illustration. We have detailed information on when production seasons and trade flows between these markets –

and hence regimes of price transmission behaviour - begin and end each year, dates which vary from year to year with variable weather conditions.

Methodology

The basic model we are concerned with is the vector error correction model (VECM) which takes the typical form:

$$\Delta p_t = \alpha\beta' p_{t-1} + \sum_{i=1}^{k}\Gamma_i \Delta p_{t-i} + \varepsilon_t = \alpha\, eqe_{t-1} + \sum_{i=1}^{k}\Gamma_i \Delta p_{t-i} + \varepsilon_t = \Pi p_{t-1} + \sum_{i=1}^{k}\Gamma_i \Delta p_{t-i} + \varepsilon_t . \quad (1)$$

$p_t = \{p_t^1, \ldots, p_t^v\}'$ and ε_t are v-dimensional vectors of prices and Gaussian white noise errors, respectively. Δ is the first difference operator so that $\Delta p_t = p_t - p_{t-1}$ and k denotes the lag length of the included price changes. The parameters of the model to be estimated are α, β and $\Gamma = (\Gamma_1, \ldots, \Gamma_k)$. The $(v \times kv)$ dimensional matrix Γ contains the partial influences of the lagged price differences on the current price changes Δp_t (hence, they are also called *short-run parameters*). The $(v \times r)$ dimensional matrix β contains the weights of the stationary long-run relationships (cointegration relationships) of the prices where r denotes the number of long-run relationships (cointegration matrix). The $(v \times r)$ dimensional matrix α is called the *loading matrix* and contains the adjustment parameters quantifying the price responses to deviations from each of the individual long run relationships, that is, the partial influences of the equilibrium deviations in the previous period on the current price movements Δp_t. The r-dimensional vector eqe_{t-1} contains these equilibrium errors, that is, the deviations from the long-run equilibrium prices of the previous period which are corrected by the price changes Δp_t from period to period. The underlying functional relationship can thus be presented as:

current price movement = f(previous equilibrium errors)+g(past price movement). (2)

In the cointegration framework, von Cramon-Taubadel (1998) based on Granger and Lee (1989) proposed estimating asymmetric price transmission processes using the following specification of the bivariate VECM ($p_t = \{p_t^1, p_t^2\}'$)[1]:

$$\Delta p_t = \alpha^+ \beta' p_{t-1} I_{t-1}^+ + \alpha^- \beta' p_{t-1} I_{t-1}^- + \sum_{i=1}^{k}\Gamma_i \Delta p_{t-i} + \varepsilon_t = \alpha^+ eqe_{t-1}^+ + \alpha^- eqe_{t-1}^- + \sum_{i=1}^{k}\Gamma_i \Delta p_{t-i} + \varepsilon_t . (3)$$

The variables I_{t-1}^+ and I_{t-1}^+ are indicator functions for the sign of equilibrium error of the previous period, that is, $I_{t-1}^+ = 1$ if $eqe_{t-1} \geq 0$ and zero otherwise, and $I_{t-1}^- = 1 - I_{t-1}^+$. However, several publications address the issue of misspecification of such a relationship, see, e.g., Gonzalez-Rivera and Helfand (2001). In particular, the pairwise analysis of prices which are subject to complex multiple influences, that is, to a multivariate system of prices might not be an appropriate modelling approach since potentially relevant variables might be omitted. This regards the omission of lagged price differences of other exogenous or endogenous prices as well as of the omission of price disequilibria which exert a significant influence.

This issue touches the question of the identification of the relevant determinants of a set of prices. One can argue that this is a disputable issue per se since one can always discuss which variables to regard and which not, that is, where and based on what criteria (theoretical considerations, significance levels, data availability, interest of the research etc.) to draw the line between included and not regarded variables. Hence, even if more than one equilibrium relationship is regarded in an equation, one can certainly argue than this increased set of

[1] For details, see, e.g., Meyer and von Cramon-Taubadel (2004) or Frey and Manera (2007).

variables might not yet represent the relevant, i.e., the true set of determinants. However, this belongs to a different aspect of model building/ variable selection since this criticism applies in exactly the same way to bivariate models such as (2). The issue addressed here is the inconsistency regarding the set of prices of interest. The attention of empirical analysis is drawn to a set of prices of a homogenous commodity recorded in more than two locations if the (potentially complex) interactions within this system of prices, that is, involving more than bivariate pairs, are to be assessed. If the modelling would focus only on bivariate price relationships, then the implicit assumption is made that all price series except the two under consideration are irrelevant[2] which contradicts the basic aim of the analysis of assessing complex interdependencies. Therefore, the model and the estimation method which we suggest allow for the consideration of all prices of the system (and all long-run equilibria between them).

Estimation Method

The suggested estimation approach is an adaptation of estimation procedure of Johansen (1988, 1990). The Johansen procedure is a three-step approach based on the concentrated version of a VECM which Johansen (1995) and Juselius (2008) call the **R-form** ('R' means *reduced*). The R-form consists of the transformed right- and left-hand side variables of the VECM in equation (1), which is referred to as the **X-form** ('X' denotes the matrix of the observed data). These variables are transformed in such a way that the estimation of all three parameters of the VECM (α, β and Γ) becomes feasible. The transformation is based on the Frisch-Waugh-Lovell Theorem (Davidson and MacKinnon, 2004: 68). The left-hand side and the right-hand side variables are purged of the partial influence of the lagged price differences Δp_{t-i}, $i = 1,\dots,k$ to create $R_{0t} = \Delta p_t - \hat{B}_0'(\Delta p'_{t-i},\dots,\Delta p'_{t-k})'$ and $R_{1t} = p_{t-1} - \hat{B}_1'(\Delta p'_{t-i},\dots,\Delta p'_{t-k})'$, where $\hat{B}_0$ and $\hat{B}_1$ are OLS estimates.

The core of the Johansen approach is a *reduced rank regression* using R_{0t} and R_{1t}:

$$R_{0t} = \alpha\beta' R_{1t} + u_t, \tag{4}$$

where u_t is normally distributed with mean vector 0 and covariance matrix Ω. Hence, model (2) becomes: *current 'purged' price movement = f('purged' previous equilibrium errors).* The approach estimates the parameters of (1) using the following three steps of which we modify the second step in order to be able to consider a multivariate regime-dependent model.

In the first step, the cointegration matrix β is estimated as derived by Johansen via $\hat{\beta} = \arg\min|\hat{\Omega}(\beta)|$ where $\hat{\Omega}(\beta)$ is the estimated covariance matrix dependent of β (Juselius, 2008). The second step estimates the loading matrix α conditional on the obtained $\hat{\beta}$ by postmultiplying (4) by $(\beta' R_{1t})' = R'_{1t}\beta$ so that one obtains $R_{0t}R'_{1t}\beta = \alpha\beta' R_{1t}R'_{1t}\beta$. Taking the average of the products of the time-dependent matrices $R_{mt}, m = 1,2$ over time generates the product moment matrices $S_{ij}, i, j = 1,2$:

$$\begin{aligned}\left(T^{-1}\sum_{t=1}^{T} R_{0t}R'_{1t}\right)\beta &= \alpha\beta'\left(T^{-1}\sum_{t=1}^{T} R_{1t}R'_{1t}\right)\beta \\ S_{01}\beta &= \alpha\beta' S_{11}\beta.\end{aligned} \tag{5}$$

These product moment matrices are used to estimate the loading matrix using OLS:

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[2] This is formalized by the fact that all other variables carry the coefficient zero or, alternatively, are dropped from the pairwise model.

$$\hat{\alpha}(\beta) = S_{01}\beta(\beta' S_{11}\beta)^{-1} \quad . \tag{6}$$

The third step of the Johansen procedure estimates the short-run dynamics Γ using equationswise OLS and assuming $\alpha\beta'$ is known.

We propose the following modification of the second step of this procedure to obtain regime-dependent estimates of the loading matrix α.[3] First, the matrix $W = \{w_t\}_{t=1,\ldots,T}$ representing any number of regimes exogenously determined by the researcher according to a set of decision rules which we refer to as the *regime indicator matrix* has to be generated.[4] It is of dimension $(T \times w)$ where w denotes the number of regimes. w_t is a $(1 \times w)$ dimensional matrix (that is, a *w*-dimensional row vector) signalling the occurrence of each of the regimes in each period *t*.

Second, the *r*-dimensional vectors $\beta' R_{1t}$ of purged equilibrium errors from (5) are 'blown up' by Kronecker multiplication from the left, that is, the regime-specific purged equilibrium errors $w'_t \otimes \beta' R_{1t}$ are of dimension $(wr \times 1)$. The matrix multiplication and the averaging over time are then done in the same way as in (5). The estimate of the matrix of adjustment speeds $\hat{\alpha}$ can then be performed identically as in (6) with the only difference that the resulting matrix is not of dimension $(v \times r)$ but of dimension $(v \times wr)$ instead. The standard errors of the regime-dependent estimates of the adjustment speeds are obtained in the usual way by only regarding the regime-dependent purged equilibrium errors $w'_t \otimes \beta' R_{1t}$ instead of the usual ones.

Hence, we reverse the order of the operations in (5) of the second step of the Johansen procedure by first multiplying by the cointegration vector and taking then averages over time. In particular, we first multiply β' and R_{1t} and obtain thus the estimated equilibrium errors of the **R-form** (the purged equilibrium errors). Afterwards, we manipulate these quantities, calculate the products of all time-dependent variables and take the averages over time last.[5]

Illustration

Consider the case in which the researcher is interested in modelling different degrees of asymmetry in different seasons, that is, seasonal APT[6] for a system of three prices connected by two long-run equilibria eqe^1 and eqe^2 (α and β are (3×2) matrices). That is, she wants to obtain estimates for regime-dependent adjustment speeds for each of eight regimes shown in the first four columns of Table 1.

In the following steps are necessary for the creation of the regime indicator matrix *W*. Indicator matrices for each of the regime categories have to be created first which signal the occurrence of a particular regime for each period *t, t=1,…,T*. Three categories exist which are the season, the sign of eqe^1 and the sign of eqe^2 all of which consist of two possible values, that is, season vs. no season and positive (≥ 0) vs. negative.

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[3] Note that both the long run relationship and the short run dynamics are assumed not to be regime-dependent,

[4] Although the regime matrix can take any dimension, more than four to six regimes would become impractical for most applied analyses.

[5] This procedure is equivalent to the one in (5). It, however, takes advantage of the reversed order since it allows the estimation of multivariate regime-dependent models.

[6] Seasonal APT might emerge in the context of developing countries due to a number of reasons. For example in the context of Sub-Saharan Africa, road and thus (potentially asymmetric) trade conditions of transport and backhaul may strongly vary by season due to differences in rainfall. Furthermore, due to strong differences in the number of traders per season, the degree of competition/ market power and thus asymmetry might differ by season.

The season indicator vector C of dimension T indicating the seasons has thus the form $C = (1\,0 \cdots 1)'$ where an element takes the value 1 if the observations belongs to the season and zero otherwise. Based on $\hat{\beta}$ from step one of the Johansen approach, the $(T \times R)$ matrix of the estimated equilibrium errors $e\hat{q}e = (\hat{\beta}' p) = p'\hat{\beta}$ can be calculated where $p = (p_1, \ldots, p_T)$ is a $(v \times T)$ matrix of observed prices. Hence, the sign indicator vectors $V^l, l = 1, \ldots, r$ signal for the l^{th} column of this matrix the signs of its elements $e\hat{q}e^l_{t-1}$ for all periods t. They are also of dimension T and have the form

$$V^l = \{v^l_t\}_{t=1,\ldots,T} \text{ where } v^r_t = \begin{cases} 1 & if\ \ e\hat{q}e^r_t \geq 0 \\ 0 & otherwise \end{cases}. \qquad (7)$$

For illustration, suppose that $e\hat{q}e = \begin{pmatrix} 1 & -2 & 3 \\ -1 & 2 & 0 \end{pmatrix}'$. The corresponding sign indicator matrices are then $V^1 = (1\,0\,1)'$ and $V^2 = (0\,1\,1)'$.

Table 1: Regime Characteristics and Regime Matrices

Regime	*Season*	eqe^1	eqe^2	*Resulting indicator vector*
A	0	>0	>0	$W^A = (I - C) \circ V^1 \circ V^2$
B	0	>0	<0	$W^B = (I - C) \circ V^1 \circ (I - V^2)$
C	0	<0	>0	$W^C = (I - C) \circ (I - V^1) \circ V^2$
D	0	<0	<0	$W^D = (I - C) \circ (I - V^1) \circ (I - V^2)$
E	1	>0	>0	$W^E = C \circ V^1 \circ V^2$
F	1	>0	<0	$W^F = C \circ V^1 \circ (I - V^2)$
G	1	<0	>0	$W^G = C \circ (I - V^1) \circ V^2$
H	1	<0	<0	$W^H = C \circ (I - V^1) \circ (I - V^2)$

Source: Authors.

Note: I denotes a T-dimensional vector of ones.

Since each regime consists of the combination of these categories, all possible combinations of the categories have to be taken into account as depicted in the last column of **Fehler! Verweisquelle konnte nicht gefunden werden.** where $\circ$ denotes the Hadamard product, that is, the element-wise product of the vectors.

The final regime indicator matrix W classifying each observation into one of the eight regimes the researcher is interested in is then the horizontal concatenation of the eight vectors in Table 1. This matrix is of dimension $(T \times w)$ and has in this case the form[7]:

$$W = \begin{pmatrix} W^A & W^B & W^C & W^D & W^E & W^F & W^G & W^H \end{pmatrix} = \{w_t\}_{t=1,\ldots,T} .$$

Data

To illustrate our proposed regime-dependent Johansen estimator, we analyse price transmission between five major tomato markets in Ghana. These are the most important net producer markets[8] Navrongo (Nav) and Techiman (Tec) which supply a substantial share of

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[7] w denotes the number of regimes, that is, in the case the above example

$w = \prod_{m=1}^{M} \text{no. of regimes of category } m = 2 \cdot 2 \cdot 2 = 8$ where M denotes the number of regime categories.

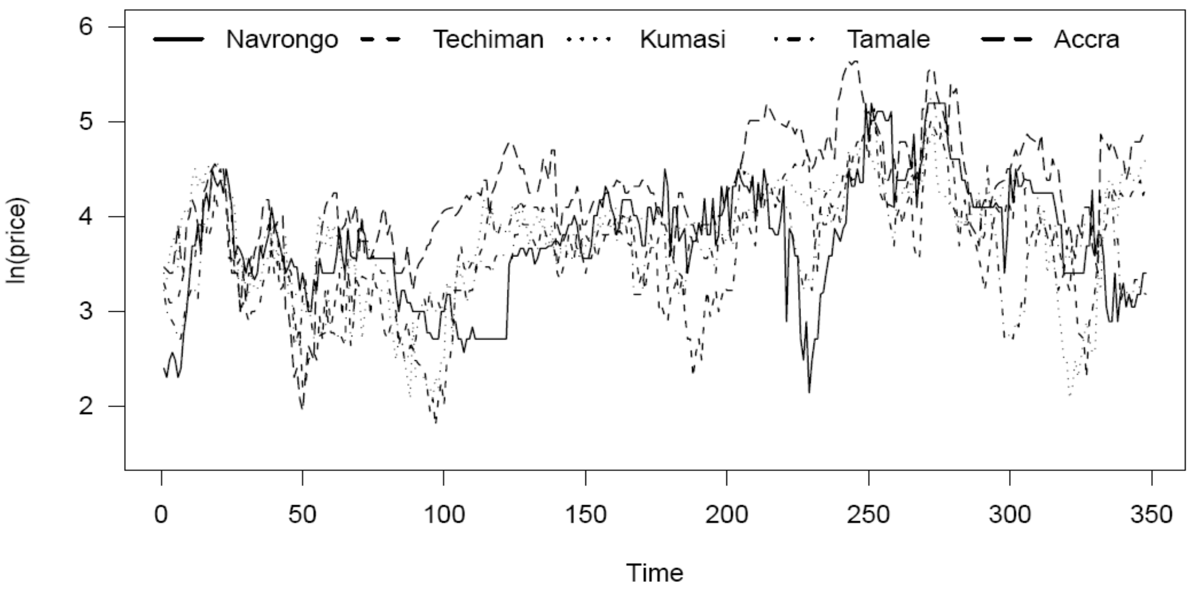
[8] We use the terms ‘net producer’ and ‘net consumer’, respectively, for regions which are characterized by net production and net consumption of tomatoes over the entire year. However, a net producer (consumer) region can import (export) during certain periods within a year.

Ghana's fresh tomato in alternate seasons, and the three most important consumer markets namely Tamale (Tam), Kumasi (Kum) and Accra (Acc), that is, the three largest urban centers in Ghana.

The analysis is based on a unique set of primary data of semi-weekly observations of wholesale tomato prices and trade flows. It was collected by continuous market surveys conducted from mid March 2007 until end of February 2010 and consists of 348 observations for each market (Figure 1). The prices are quoted for the best quality of tomato available at the time of the survey in the given market. They are measured in New Ghana Cedis (GH¢) per 100 kg crate of fresh and ripped tomato, which is the standard unit of tomato trade in Ghana. The analysis is carried out on prices in logarithms.

Due to differences in the weather conditions that prevail in the two main producer markets, tomato production in Ghana is highly seasonal. The producer market Navrongo, located in the northern savannah region and dependent on irrigated production, is the main source of tomato supply in the dry season (December – May).[9] Techiman, located in the southern forest region and using a rain-fed production system, supplies the national market with tomatoes in the rainy season (June- November). In between the two main domestic supply seasons is a short transitional period (May – June) within which much of the tomato supply in Ghana is provided by imports from Burkina-Faso. However, since no tomato wholesale prices from Burkina Faso are available, we regard this in-between period and the Navrongo season as one season. Since Navrongo is located close to the border with Burkina Faso on the major trade route that connects the two countries, we expect that tomato trade patterns in the rest of Ghana will be similar regardless of whether Navrongo itself is exporting or acting as a conduit for tomatoes from Burkina Faso. Altogether, the dataset covers a sequence of seven seasons, which are alternating between Techiman and Navrongo, over a three year period.

Figure 1: Prices of Fresh Tomato in Ghana in GH¢



Source: Authors.

During the Navrongo season, the region in the north of Ghana supplies about 80%[10] of all fresh tomato traded in Ghana. About three months following the onset of tomato supply from

[9] The exact timing and duration of each season changes from year to year depending on weather conditions.

[10] Due to lack of reliable data on the quantities of production and supply, the stated percentages are only approximate market shares based on observations.

Navrongo, the market's output levels begin to decline and its share of tomato in the markets gradually phases out while imports from Burkina-Faso into Ghana increases. As supply of fresh tomatoes from Navrongo declines, the supply of tomato from Burkina-Faso increases, peaking at about three quarters of the share of fresh tomato marketed in Ghana in April and May. High transaction costs due to the long distance to the huge consumer markets in Ghana's south and the "cross-border" location of Burkinabe tomato markets lead to high tomato prices in Ghana which tend to rise continuously from the start to the end of this period. Techiman is by far the largest supplier of Ghana's fresh tomatoes, supplying tomato for more than six months a year. Due to the rain-fed production and the increased perishability of tomato during the rainfall season, the average price of the commodity is generally lowest during this period. Furthermore transportation costs may be higher since rainfall makes roads to farm gates less passable.

Based on the above thoughts and the market characteristics, we aim at assessing a multivariate regime-dependent model for the Ghanaian tomato market. Although the approach outlined above allows for a highly complex multivariate structure we stick for illustrative purposes to a parsimonious model. One might imagine a model assessing asymmetry in each of the equilibrium relationships between 4 prices, that is, yielding four equilibrium errors. This would lead to a model of eight regimes leaving on average only less than 45 observations for each regime. We consider this number as too low to yield stable estimation results and thus stick to a model with only four regimes, that is, having on average 90 observations per regime. As mentioned above, Techiman and Accra are the most important producer and consumer markets, respectively. Thus, we hypothesize that the long-run equilibrium between these plays a crucial role in the national Ghanaian tomato market. Consequently, price disequilibria in this relationship may signal price shocks which are relevant for the whole market system. That is why, we analyse the impact of asymmetry in this price relationship on the entire Ghanaian market. Furthermore, we take the seasonal structure of the market explicitly into account because it represents a major feature which is likely to shape spatial price dynamics in the country.

Thus, we propose the following multivariate APT model:

$$\Delta p_t = \alpha^A eqe_{t-1}^A + \alpha^B eqe_{t-1}^B + \alpha^C eqe_{t-1}^C + \alpha^D eqe_{t-1}^D + \sum_{i=1}^{k} \Gamma_i \Delta p_{t-i} + \varepsilon_t . \tag{8}$$

The indices A to D indicate the four regimes considered (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Each of the vectors $eqe_{t-1}^i = \left(eqe_{t-1}^{i1} \quad eqe_{t-1}^{i2} \quad eqe_{t-1}^{i3} \quad eqe_{t-1}^{i4} \right)', i = A, B, C, D$ has four elements (that is, four equilibrium errors per regime where 1 denotes the equilibrium Nav-Acc, 2 Tec-Acc, 3 Kum-Acc and 4 Tam-Acc) so that each of the matrices α^i has five rows and four columns. The resulting vector of deviations from equilibrium consisting of the four stacked equilibrium error vectors is thus of dimension $wr = 4 \cdot 4 = 16$ and the final loading matrix of regime-dependent adjustment speeds has $(v \times wr) = (5 \times 16)$ elements. The signs of the equilibirum deviations for the market pair Techiman and Accra are obtained according to (7), and we use information on the direction of trade flows between the markets in Ghana to determine when the Techiman and Navrongo seasons begin and end in each individual year. Tests and estimations were performed using JMulTi (Lütkepohl and Krätzig, 2004), R (R Development Core Team, 2009) and the urca-Package for R (Pfaff, 2008).

Estimation Results

Time Series Properties

We first test for unit roots in the individual price series and for their cointegration rank by using the KPSS test[11] (Kwiatkowski et al., 1992) and the Johansen trace test, respectively. At the 5% level of significance, the KPSS test clearly suggests that all five series have a unit root. Furthermore, we obtain strong evidence that there are four cointegration relationships (long-run price equilibria) among the five price series.[12] In other words, the price system is driven by a single common stochastic trend. In view of this, and since we observe trade flows between the five markets in all periods, we conclude that the markets are integrated as defined by Gonzalez-Rivera and Helfand (2001).

Table 2: Regimes of Multivariate APT

Regime	*Deviation from the Tec-Acc equilibrium*	*Season*	*Frequency*
A	Positive	Techiman	31%
B	Positive	Navrongo	21%
C	Negative	Techiman	29%
D	Negative	Navrongo	19%

Source: Authors.

Regime-dependent Johansen Estimation

We first estimate a multivariate VECM[12] and obtain the following not regime-dependent relationships[13] by applying a number of restrictions on the cointegration relationships $e\hat{q}e_t^1 = p_t^{Nav} - p_t^{Acc} + 0.462$, $e\hat{q}e_t^2 = p_t^{Tec} - 1.15 p_t^{Acc} + 1.24$, $e\hat{q}e_t^3 = p_t^{Kum} - p_t^{Acc} + 0.435$ and $e\hat{q}e_t^4 = p_t^{Tam} - p_t^{Acc} + 0.571$.

The signs of only the second equilibrium error $e\hat{q}e_t^2$ are used to create the sign indicator matrices which yields in combination with the season indicator vector the four regimes as outlined in **Fehler! Verweisquelle konnte nicht gefunden werden.**. Table 3 displays the regime-dependent estimates of the adjustment speeds. It clearly suggests that the dynamics of price adjustment appear to differ considerably across the four regimes that we hypothesised in the Ghanaian tomato market. They appear to be particularly relevant for the two producer markets which are significantly affected by multiple asymmetric partial influences in all four regimes. In contrast, the three consumer markets only show very few significant reactions to disequilibria and appear to be weakly exogenous in most regimes.

In general, the adjustment speeds are large in magnitude. This points to very fast adjustment of existing disequilibria which is plausible given that tomatoes are perishable and the very good state of the arterial West African Highway connecting the market centres in the north and the south of the country. It suggests furthermore that networks of tomato traders are well evolved since they obviously permit very quick responses to price shocks throughout the country.

Moreover, we observe that the adjustment speeds in the first, fifth and ninth row of the Navrongo price and in the second, the tenth and the fourteenth row of the Techiman price are

[11] This test has the null hypothesis that the series is stationary. If the test statistic exceeds the critical value, then the null is rejected. We test for level stationarity for all series except Accra because it is the only series which shows, based on visual inspection, slight trending. In the selection of the lag length, we follow the recommendation of Kwiatkowski et al. (1992: 175) and use $8(348\ /100\ )^{0.25} \approx 11$ lags.

[12] Detailed results can be obtained from the authors upon request.

[13] The Wald test for the adequacy of these restrictions yields a p-value of 0.12 so that the restrictions are cannot be rejected at the 5% level.

the price responses (the partial impacts) to deviations from the equilibria of each price with Accra all of them being significant at 5%. They are extraordinarily strong in magnitude and all of the correct sign. That is, disequilibria in the Nav-Acc and the Tec-Acc relationships are very quickly corrected by the prices of the respective producer market. Significant price responses are even observed in the off-season of the respective market, that is, in regimes *B* and *D* for the Techiman and regimes *A* and *C* for the Navrongo price. This appears to be a very plausible observation in the Ghanaian tomato market given the strong evidence for market integration as found above and the particular spatial structure of the markets along the West African Highway.

The magnitudes of the four significant reactions of the producer markets are also of correct sign. The price of the huge consumer market of Ghana's capital significantly and very strongly responds to positive deviations from its equilibrium with Techiman during the Navrongo season (regime *B*) as can be seen in the sixth row of Accra (coefficient 0.304). At the 5% level of significance, the Navrongo price shows five significant responses (rows 2, 7, 8, 12 and 15) to disequilibria additionally to the above-mentioned three responses to deviations from its own equilibrium. A similar pattern is shown by the Techiman price in rows 3, 13 and 15. These equilibrium deviations lead to an increase of the Navrongo and Techiman price, respectively, and thus tend to push these prices away from their respective equilibria with respect to Accra. They thus counteract the correction of equilibrium errors indicated by the strong adjustments in rows 1, 5 and 9 and in rows 2, 10 and 14 for the Navrongo and Techiman price, respectively. Since they increase the disequilibrium, these coefficients show that disequilibrium spills over from one market to another in the system in the short-run.

Table 3: Estimates of the Regime-dependent Adjustment Speeds α

Regime	*Equilib. Error*[A]	*Navrongo*	*Techiman*	*Kumasi*	*Tamale*	*Accra*
A	Nav-Acc	-0.421***	0.009	0.039	-0.02	0.106
A	Tec-Acc	0.293**	-0.336***	0.012	0.062	-0.087
A	Kum-Acc	0.088	0.127**	-0.078	-0.002	0.037
A	Tam-Acc	0.058	0.086*	-0.013	-0.119**	-0.007
B	Nav-Acc	-0.132**	-0.02	0.008	0.084	0.002
B	Tec-Acc	-0.137	-0.181*	0.116	0.05	0.304***
B	Kum-Acc	0.266***	0.055	-0.107	0.085	-0.032
B	Tam-Acc	0.208**	0.059	-0.007	-0.134	0.065
C	Nav-Acc	-0.257***	0.089	-0.088	0.063	0.034
C	Tec-Acc	-0.112*	-0.124**	0.035	-0.063	0.071
C	Kum-Acc	0.12*	0.100*	0.041	0.022	0.086
C	Tam-Acc	0.136**	0.007	0.115**	-0.111*	0.057
D	Nav-Acc	-0.126*	-0.129**	-0.039	0.039	0.016
D	Tec-Acc	-0.225*	-0.448***	0.06	-0.078	-0.021
D	Kum-Acc	0.259**	0.339***	-0.133	0.085	0.035
D	Tam-Acc	0.084	0.202*	0.036	-0.169	-0.02

Source: Authors' calculations.

[A] For clarity, we do not write here the symbols (such as $e\hat{q}e_t^{11}$ etc.) but instead the names of the markets of the respective equilibrium. Note: The asterisks ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

Conclusions

This article proposes an extension for modelling regime-dependent behaviour of price responses to disequilibria to the multivariate context. In particular, it extends the traditional bivariate analysis of the asymmetric price transmission model to a multivariate approach, that is, to a model which is capable to account for more than two price series, more than one cointegration relationship and to regard more than one regime-classifying category. It is not restricted to one rule for regime-classification, e.g., only the sign of the equilibrium error, but may consider more than one regime category or even a combination of such categories, e.g., seasonal asymmetric price dynamics. For the estimation of such multivariate regime-dependent price transmission models, we propose a methodological innovation since to date, to our knowledge, either the Engle-Granger or the Stock-Watson methodologies are used for estimation. We modify the the Johansen estimation method, the preferred method for cointegration modelling (Gonzalo, 1994). It allows the estimation of regime-dependent loading matrices using the Johansen method in cases where exogenous information about the duration of regimes (seasons, the signs of the equilibrium deviations, etc.) is available. We explain in detail how the standard estimation approach can be adapted in order to benefit from its desirable statistical properties also in this context.

This theoretical part is accompanied by an application of the method which demonstrates its the feasibility, strengths and weaknesses. We analyze a unique set of semi-weekly price data of the tomato market of Ghana in order to assess seasonal asymmetric price dynamics. We regard the five most important regional markets – a network which is characterized by complex price dynamics and interdependencies. We find that the prices show pronounced regime-dependent adjustment behaviour. Strongest responsiveness to disequilibria, that is, error-correction, is shown by the two production regions of Techiman and Navrongo with the price of the smaller market showing manifold reactions on deviations from various equilibria in all regimes. Furthermoe, evidence for short-run disequilibria spill overs is obtained.

This analysis not only provides a methodological extention of a modelling strategy and an estimation method, but also an informative insight into price dynamics in the tomato market of Ghana. Although the primary data might suffer from some measurement error, they constitute a unique setting for the analysis of price transmission of a perishable agricultural commodity in Sub-Saharan Africa. The general picture suggested by the analysis appears to be plausible given the structure of the country’s tomato market.

This research can be extended in various ways. The statistical properties of the suggested estimator have to be assessed in detail in future research. It has to be carefully checked whether the preferable properties of the Johansen estimator also hold for the proposed modification, that is, how the method performs in direct comparison with the Engle-Granger or the Stock-Watson methodologies. Also the question of the minimum number of observations necessary in each regime in order to obtain stable results has to be answered. Furthermore, a number of tests on the estimated regime-dependent adjustment speeds may be performed straightforwardly in the framework of the Johansen methodology. Last, the estimation of regime-dependent impulse response functions or similar measures might supplement the presented estimation results.

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