Agricultural Systems xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Distinguishing between endogenous and exogenous price volatility in food security assessment: An empirical nonlinear dynamics approach

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A R T I C L E I N F O

Article history:
Received 19 October 2015
Received in revised form 26 September 2016
Accepted 29 September 2016
Available online xxxx

Keywords:
Food security
Price volatility
Phase space reconstruction

A B S T R A C T

We propose an empirical scheme—based on nonlinear dynamics—for diagnosing real-world market dynamics from observed price series data. The scheme distinguishes between endogenous and exogenous volatility in observed price series, tests whether endogenous volatility is generated by low-dimensional deterministic market dynamics, simulates these dynamics with a phenomenological market model, and models extreme volatility probabilistically. These diagnostics allow policymakers to make an empirically-informed determination of whether laissez-faire or interventionist policies are most promising in reducing price volatility in particular cases. We apply the diagnostic scheme to provide compelling empirical evidence that observed volatility in organic apple, pear, orange, and lemon prices at the Milano (Italy) Ipercoop is due to endogenous market dynamics governed by low-dimensional nonlinear behavior. The implication for food policy is that this inherently unstable market cannot be relied upon to systematically stabilize observed price volatility from random exogenous shocks. There may be scope for public interventions targeted to increasing the flexibility of organic fruit producers in responding to changing market conditions.

1. Introduction

Key international agencies and think tanks identify food-price volatility as a serious threat to food security (G20 2011; HLPE 2011; Kalkuhl et al. 2013). Policies broadly seek to reduce price volatility itself and/or buffer its negative impacts on consumers and producers through market-based strategies or public interventions (Galtier 2013; Gouel 2012). Market-based strategies are intended to reduce price volatility by improving market allocation of commodities spatially (through trade) and temporally (through storage), and to buffer negative impacts on producers through risk-hedging instruments in futures markets and, to a limited extent, on consumers through emergency aid during food crises. Public interventions are intended to reduce price volatility by controlling available market quantities with tools including price floors/ceilings, quantity restrictions, taxes and subsidies, and public buffer stocks, and to buffer negative impacts with transfer payments designed to protect producer incomes during periods of low prices and consumer's access to food levels during periods of high prices (Galtier 2013).

The consensus in the literature is that the effectiveness of public interventions depends on the agricultural price dynamics driving volatility. The dominant doctrine attributes volatility to exogenous random shocks that price adjustments dampen over time (Galtier 2013). In this framework, public interventions interfere with the market's 'natural correction process' (Gouel 2012). An alternative explanation is that price volatility persists in recurrent patterns due to the endogenous behavior of inherently unstable food markets responding to changes in supply and demand (Berg and Huffaker 2015; Chavas and Holt 1993; Galtier 2013). Agricultural markets do not provide a 'natural correction process' for price volatility.

Galtier (2013) concludes that distinguishing between endogenous and exogenous price volatility in particular agricultural markets "is still an open question, and the only certitude we have is that endogenous sources of instability can theoretically exist and affect all countries, with panics being far more probable…" (p. 74). In this paper, we propose a five-stage empirical diagnostic scheme—based on nonlinear dynamics techniques—to distinguish between endogenous and exogenous market dynamics in observed agricultural price series. Armed with this empirical evidence, policymakers can make an empirically-informed determination of whether laissez-faire or interventionist policies might be more effective in managing price volatility in particular cases.

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http://dx.doi.org/10.1016/j.agsy.2016.09.019

2. Past empirical approaches

Gouel (2012) surveys two main approaches that have been used to empirically distinguish between endogenous and exogenous food price volatility. A 'model-centric' approach tests for endogenous volatility by directly estimating theoretical market models. Models that fit the data well and/or conform to 'stylized facts' based on statistical properties of observed agricultural prices are deemed to provide empirically-validated explanations for endogenous volatility. An alternative 'data-centric' approach seeks to establish positive empirical evidence that observed volatility is generated endogenously by a particular type of nonlinear dynamics: low-dimensional chaos (Adrangi and Chatrath 2003; Chatrath et al. 2000).

The major problem with a model-centric approach is that a theoretical model cannot be validated by demonstrating a 'good fit' with observed data since other models with very different structures and representations of reality can be parameterized to also provide good fits (Hornberger and Spear 1981; Oreskes et al. 1994; Rykiel 1996). The commodity price literature provides an instructive case study. The empirical validity of the classic competitive storage model was challenged on the basis that it failed to account for the degree of serial correlation in observed commodity prices (Deaton and Laroque 1996). However, subsequent work demonstrated that a competitive storage model could be reformulated to improve empirical performance (Cafiero et al. 2011), and moreover that the measurement of price data used to estimate a given model could impact empirical performance (Guerra et al. 2015).

An additional problem with a model-centric approach is that the conformity of model output with 'stylized facts' based on probabilistic properties of observed prices does not resolve the price endogeneity question. The methodological standard set in the empirical nonlinear dynamics literature compares model dynamics with those empirically reconstructed from observed data based on shared topological properties (Kot et al., 1988).

An alternative data-centric approach—seeking positive evidence of endogenous chaotic dynamics in commodity price data—is also unreliable. The approach proceeds as follows: First, a price series is purged of linear dynamics and seasonal variation with a linear-autoregressive (ARCH/GARCH) model. Next, a phase-space attractor is reconstructed from the filtered price series using time-delay embedding (Takens 1980), and tested for topological features of chaos including 'self-similar geometry' (by measuring the correlation dimension), and 'sensitive dependence on initial conditions' (by measuring the Lyapunov exponent). The major drawback with relying on these measures to positively demonstrate chaotic dynamics in observed data is that they are based on asymptotic properties best met with vast amounts of high quality data provided by laboratory experiments designed specifically for investigating chaos (Schreiber 1999). The measures are unreliable when estimated from short and noisy real-world data (Chatrath et al. 2000; Schreiber 1999).

These topological measures perform reliably when the focus of empirical nonlinear analysis is relaxed from attempting to demonstrate the presence of deterministic chaos in observed data to gauging the degree to which endogenous nonlinear dynamics are present (Schreiber 1999; Schreiber and Schmitz 2000). Our proposed empirical nonlinear diagnostic scheme follows this path.

We apply nonlinear diagnostics to empirically reconstruct and characterize the dynamics of an organic fruit market from volatile organic apple, pear, orange and lemon prices (Euros per kilogram, €/kg) recorded weekly at the Milano Ipercoop over an eight-year interval (from 2003 to 2010, 421 weeks). The Ipercoop is the largest store format of the leading retail grocery chain in Italy (COOP)—a consumer cooperative with about 15% of the market share. Price data were provided by the Centro Servizi Ortofrutticoli (CSO), a cooperative company based in Ferrara (Italy), whose members are companies working in all phases of the fruit and vegetable supply chain. CSO collects weekly retail price data at selected stores in Italy and Europe. Consequently, the prices represent the evolution of a niche organic fruit market serving a limited number of consumers to a common retail market with widespread distribution (Canavari et al. 2002; Canavari and Olson 2007). We find strong empirical evidence that price volatility in the organic fruit market investigated is endogenously generated by nonlinear, low-dimensional and deterministic market dynamics.

How can we hope to reconstruct full market dynamics from observed price series? The answer is that the evolution of each price series encodes the historical interactions of driving market forces including consumer demand, fruit production, input costs, contracting practices, and so on; and nonlinear diagnostics recover this encoded information. The organic fruit price series used in this work illustrate well how market dynamics can be reconstructed from price data, and how reconstructed dynamics can guide subsequent formulation of realistic mechanistic market models using techniques such as dynamic systems modeling. The actual formulation of a mechanistic market model is beyond the scope of this paper.

3. An empirical nonlinear dynamics diagnostics scheme

We diagnose endogenous market dynamics as a source of observed price volatility as follows (Fig. 1): In Stage 1, we apply *Singular Spectrum Analysis* to separate each price series into endogenous structured volatility ('signal') and exogenous unstructured volatility ('noise') with signal processing techniques. In Stage 2, we test whether a detected signal is generated endogenously by nonlinear, low-dimensional and deterministic market dynamics with *Nonlinear Time Series Analysis* (Kantz and Schreiber 1997). In Stage 3, we conduct causal network analysis with *Convergent Cross Mapping* (Sugihara et al. 2012) to empirically test whether the dynamics of the observed organic fruit prices causally interact in the same market system. If so, in Stage 4, we simulate empirically-detected endogenous price volatility with a dynamic (phenomenological) market model composed of a system of ordinary differential equations (Baker et al. 1996), and use the model to investigate dynamic price interactions driving endogenous market dynamics. Finally, in Stage 5, we model exogenous noise with *Extreme Value Statistics* (Katz 2010)—a method currently used in the food security literature (Kalkuhl et al. 2013).

3.1. Signal processing

We apply *Singular Spectrum Analysis*—a 'data driven' signal processing method that accommodates highly anharmonic (potentially non-sinusoidal) oscillations in irregular time series data (Elsner and Tsonsis 2010)—to separate an observed price series into endogenous structured variation ('signal') and exogenous unstructured variation ('noise'). Signal incorporates trend and oscillatory components. Signal strength is measured as the fraction of variation explained in an observed price series from its mean when the price series is converted to an anomaly from its mean, and the *Toeplitz* method of *SSA* is applied (Ghil et al. 2002; Golyandina et al. 2001). Signal strength provides preliminary empirical evidence for the relative contribution of endogenous to exogenous volatility. Positive (negative) noise levels occur at times when an observed price series is greater (less) than the corresponding signal.

Singular Spectrum Analysis can be applied to fill in intermittent missing values in observed data by using dynamic structure detected from the full range of reported observations to calculate replacements for missing values. Consequently, it processes more information than conventional moving average approaches limited to observations immediately surrounding the missing values (Golyandina et al. 2001).

3.2. Nonlinear time series analysis

We apply *Nonlinear Time Series Analysis* (*NLTS*) (Kantz and Schreiber 1997) to test whether structured volatility separated in signal

Please cite this article as: Huffaker, R., et al., Distinguishing between endogenous and exogenous price volatility in food security assessment: An empirical nonlinear dynamics appr..., Agricultural Systems (2016), http://dx.doi.org/10.1016/j.agsy.2016.09.019