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Asset Prices in a Small Production Network*

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Abstract

This paper constructs an asset pricing model where heterogeneous sectors interact with each other in a production network as producers and consumers of materials and investment goods. Idiosyncratic sectoral shocks are transmitted through the network with the dynamics being affected by the heterogeneity in production functions and capital adjustment costs. The model is estimated using sectoral and aggregate U.S. data. Results show that 1) shocks to the primary sector account for a substantial part of the equity premium in all sectors because their volatility is much higher than that of shocks to the other sectors, and 2) the model endogenously generates conditional heteroskedasticity despite the fact that shocks are conditional homoskedatic. These results depend crucially on the presence of network effects.

JEL Classification: E44, G12

Key Words: Network, input-output, production economy, stock returns, sectoral shocks.

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1. Introduction

This paper studies asset pricing in a production economy where heterogenous sectors subject to idiosyncratic shocks interact with each other in a network. Interactions takes place directly from the production and consumption of materials and investment goods, and indirectly from the fact that the consumption bundle purchased by households is composed of goods produced by all sectors. The focus is on the implications of sectoral heterogeneity and network interactions for sectoral stock returns and on the transmission of sectoral disturbances to real and financial variables of all sectors through the network.

In this paper I consider the simplest possible network with three sectors, namely a primary sector that produces raw materials, manufacturing, and services. Three is the minimal number of sectors with nontrivial interactions between sectors. The deliberate choice of working with a small network allows me to construct and estimate a rich model with multiple sources of heterogeneity and to fully examine its time-series implications.[1] Estimates show substantial heterogeneity in production functions, capital adjustment costs, and the volatility of productivity innovations across sectors. In particular, the standard deviation of shocks to the primary sector is one order of magnitude larger than to manufacturing and services, which in turn are one order of magnitude larger than the standard deviation of aggregate productivity shocks.

Using impulse-response analysis, I trace out the propagation of sectoral shocks through the network and their effect on sectoral and aggregate variables. I find that heterogeneity in capital adjustment costs and in network interactions induce different sectoral dynamics across sectors in response to the same shock. The large volatility of shocks to the primary sector and their propagation through the network play a key role in the financial variables all sectors despite the fact that this sector is small and does not produce capital goods. I show that shocks to the primary sector account for around 16% of the equity risk premia in both manufacturing and services. In contrast, in a model without network interactions shocks to the primary sector account for only 0.05% of the equity risk premia in these sectors.

Finally, I find that the nonlinear asset-pricing model can endogenously generate conditional heteroskedasticity in sectoral stock returns and excess returns despite the fact that shocks are conditionally homoskedastic. However, the results that stock returns and excess return in manufacturing and services are conditionally heteroskedastic crucially depends on modeling network interactions.

[1] As part of this research agenda, a companion paper (Ruge-Murcia, 2018) studies the cross-section implications of the model using data at a higher level of disaggregation with 30 sectors at the two-digit level of the North American Industry Classification System (NAICS).

This paper contributes to two branches of the literature on asset pricing. First, this paper contributes to the macro-finance literature that studies asset pricing in production economies. This literature is generally concerned with aggregate stock returns and models production as taking place in a representative firm subject to an aggregate productivity shock. Important contributions include Cochrane (1991), Rouwenhorst (1995), Jermann (1998), Tallarini (2000), Campanale et al. (2010), and Croce (2014). Compared to this literature, the focus here is on sectoral, rather than on aggregate, stock returns. To that end, I relax the assumption that all firms are identical and subject to the same shocks and assume instead that firms belong to one of a finite number of sectors. Firms in the same sector are identical, but firms in different sectors have different production functions, use different combinations of materials and investment goods to produce their output, face difference costs to adjust their capital stock, and are subject to idiosyncratic productivity shocks with different persistence and volatility. Firms in different sectors interact with each other in the market for intermediate inputs and investment goods in a manner consistent with the U.S. input-output accounts. This model builds on research that studies business cycles in multi-sector economies (e.g., Horvath, 1998, and, specially, Bouakez et al., 2009), but focuses instead on the asset-pricing implications of sectoral heterogeneity and differs methodologically by going beyond standard linear solutions. I show that nonlinearity is important, for instance, to generate conditional heteroskedasticity endogenously.

Second, this paper contributes to the finance literature on network effects on asset prices. Recent contributions include Buraschi and Porchia (2012), Ahern (2013), Herskovic (2015), and Ramirez (2017). These papers work at a very high level of disaggregation and focus the role of centrality (that is, the number of connections with other sectors) in asset prices. Ahern finds that more central firms have higher stock returns because they are more exposed to sectoral shocks through inter-sectoral trade. Ramirez finds that more central firms command a lower risk premia because of a greater diversification in customers and suppliers. My research complements their work by exploring the role of sources of heterogeneity other than network centrality on sectoral stock returns. For instance, I show that heterogeneity in the volatility of sectoral shocks is important to understand equity risk premia in different sectors.

The paper is organized as follows. Section 2 presents the production and consumption network, and describes the nonlinear solution method used to solve model. Section 3 presents the data and econometric strategy, and reports the parameter estimates. Section 4 reports the results from the analysis. Finally, Section 5, concludes.

2. The Network

This section describes an economy where firms in different sectors produce different goods using different combinations of materials and investment goods. Firms interact directly with each other in the market for intermediate goods and indirectly in the market for final goods consumed by households.

2.1 Production and Intermediate Consumption

Production is carried out by perfectly competitive firms in each of $S = 3$ heterogenous sectors. The sectors produce raw materials, manufactured goods, and services, respectively. The representative firm in sector $s \in S$ uses the technology

$$y_t^s = z_t^s (z_t n_t^s)^{\eta^s} (K_t^s)^{\alpha^s} (M_t^s)^{\theta^s}, \tag{1}$$

where y_t^s is output, z_t^s and z_t are productivity shocks, n_t^s is labor, K_t^s is capital, M_t^s is materials, and $\eta^s, \alpha^s, \theta^s \in (0,1)$ are parameters. The shock z_t^s is sector-specific and affects only the firms in sector s, while the shock z_t is aggregate and affects all firms in all sectors simultaneously. The technology is constant returns to scale and, hence, $\eta^s + \alpha^s + \theta^s = 1$.

The capital stock is owned by firms while labor is rented from households at the rate w_t^s. Materials are purchased from all sectors and combined according to

$$M_t^s = \prod_{i=1}^{S} \zeta_{is}^{-\zeta_{is}} (m_{i,t}^s)^{\zeta_{is}}, \tag{2}$$

where $m_{i,t}^s$ is the quantity of good purchased from sector i and $\zeta_{is} \geqslant 0$ are weights that satisfy the restriction $\sum_{i=1}^{S} \zeta_{is} = 1$. The price of M_t^s is $Q_t^{M^s} = \prod_{i=1}^{S} (p_t^i)^{\zeta_{is}}$, where p_t^i is the price of good i. The production structure is round-about meaning that all sectors use materials from all sectors. However, the weights vary across purchasing sectors and, thus, each sector uses a different combination of materials to produce its output. In the empirical part of this paper, the weights ζ_{is} are computed from the Use table of the U.S. Input-Output (I-O) accounts and, hence, the flows of materials across sectors will be in line with those observed in the data.

Investment goods are also purchased from all sectors and combined according to

$$X_t^s = \prod_{i=1}^{S} \kappa_{is}^{-\kappa_{is}} (x_{i,t}^s)^{\kappa_{is}}, \tag{3}$$

where $x_{i,t}^s$ is the quantity of good purchased from sector i and $\kappa_{is} \geqslant 0$ are weights that satisfy the restriction $\sum_{i=1}^{S} \kappa_{is} = 1$. The price of X_t^s is $Q_t^{X^s} = \prod_{i=1}^{S} (p_t^i)^{\kappa_{is}}$. Since the weights vary across purchasing sectors, the aggregate X_t^s is a sector-specific combination of investment goods. The special case where $\kappa_{is} = 0$ covers the situations where 1) the sector i does not produce any investment good or 2) it produces investment goods but they are not useful in the production of good s. In the empirical part of this paper, the weights κ_{is} are computed from the Capital Flow table of the I-O accounts and, thus, the flows of investment goods across sectors and the composition of sectoral capital stocks will be in agreement with those in the data.

The investment aggregate X_t^s is added to the current capital stock (net of depreciation) to form the capital that will be used in production in the next period. That is,

$$K_{t+1}^s = (1-\delta)K_t^s + X_t^s - \Gamma_t^s, \tag{4}$$

where $\delta \in (0,1)$ is the rate of depreciation. The function Γ_t^s represents the cost of installing or uninstalling additional units of capital and it is assumed to have the convex form

$$\Gamma_t^s = (\chi^s/2)\left(X_t^s/K_t^s - \delta^*\right)^2 K_t^s, \tag{5}$$

where $\chi^s \geqslant 0$, $\delta^* = \delta + (\varsigma - 1)$, and $\varsigma > 1$ is the average gross rate of growth of the economy. Capital adjustment costs permit variations in Tobin's q over time and across sectors and limit the households' ability to smooth the volatility of marginal rates of substitution (see Jermann, 1998). Note that the functional form (5) implies that capital adjustment costs in the steady state are zero.

Sectoral interactions are not summarized here using a single network (e.g., as in Ahern, 2013 who constructs a social accounting matrix that incorporates trade flows across all industries, consumers, and the government.) Instead, sectors here interact differently in the markets for materials, investment goods, and consumption goods. I follow this modeling strategy for two reasons. First, technology and the nature of the goods i and s require the weights ζ_{is} and κ_{is} to be different. In particular, we will see in the empirical section of the paper that the Use table has relatively large diagonal entries—meaning, for example, that services are a large provider of materials for the production of services—, while the Capital Flow table is sparse and has large entries in the row corresponding to manufacturing because most investment goods are produced by this sector. Second, the difference in sectoral interactions in the markets for material and investment goods has dynamic implications because materials are used within the period but investment goods can be transferred intertemporally in the form of capital.

The representative firm maximizes

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{t-\tau} \Lambda_{\tau,t} d_t^s, \tag{6}$$

where E_t is the expectation conditional on information available at time τ, $\beta \in (0,1)$ is the discount factor, $\Lambda_{\tau,t}$ is the ratio of the shareholders' marginal utilities between periods t and τ, and d_t^s is profits. Profits are total revenue minus total costs,

$$d_t^s = p_t^s \left(c_t^s + \sum_{j=1}^{S} x_{s,t}^j + \sum_{j=1}^{S} m_{s,t}^j \right) - \left(w_t^s n_t^s + \sum_{i=1}^{S} p_t^i x_{i,t}^s + \sum_{i=1}^{S} p_t^i m_{i,t}^s + \Gamma_t^s Q_t^{X^s} \right), \tag{7}$$

where c_t^s is final consumption by households, and $x_{s,t}^j$ and $m_{s,t}^j$ is intermediate consumption by sector j in the form of investment good and materials input, respectively. Notice that final and intermediate goods are physically the same good and differ only by whether they are consumed by households or by firms to produce other goods.[2] The firm takes as given the demand functions by households and other firms. The costs are the wage bill, total expenditures on capital goods, total expenditures on materials inputs, and the cost incurred by adjusting the capital stock. Firms do not issue new shares and, thus, all investment is financed through retained earnings. Since the production function is constant returns to scale and firms are perfectly competitive, profits are simply the return on capital net of investment and adjustment costs. In every period, profits are transferred to shareholders in the form of dividends.

The consumption of materials produced by sector i is the solution to

$$\max_{\{m_{i,t}^s\}} \prod_{i=1}^{S} (\zeta_{is})^{-\zeta_{is}} (m_{i,t}^s)^{\zeta_{is}}, \tag{8}$$

subject to the constraint that $\sum_{i=1}^{S} p_t^i m_{i,t}^s$ equals a given expenditure level. The solution is

$$m_{i,t}^s = \zeta_{is} Q_t^{M^s} M_t^s / p_t^i. \tag{9}$$

Note that $\sum_{i=1}^{S} p_t^i m_{i,t}^s = Q_t^{M^s} M_t^s$. Similarly, the consumption of investment goods produced by sector i is

$$x_{i,t}^s = \kappa_{is} Q_t^{X^s} X_t^s / p_t^i, \tag{10}$$

with $\sum_{i=1}^{S} p_t^i x_{i,t}^s = Q_t^{X^s} X_t^s$. Due to the assumption of Cobb-Douglas aggregators in (2) and (3), the expenditure shares of capital goods and materials inputs produced in sector i are constant and equal to the weights κ_{is} and ζ_{is}, respectively.

[2] For instance, in the same way that a car is a final good if purchased by a household and an intermediate good if purchased by a leasing firm for the purpose of producing car rentals.

2.2 Final Consumption

Households are identical, infinitely-lived, and their total number is normalized to be 1. The representative household has recursive preferences over consumption (Epstein and Zin, 1989),

$$U_t = \left((1-\beta)\,(C_t)^{1-1/\psi} + \beta \left(E_t \left(U_{t+1}^{1-\gamma} \right) \right)^{(1-1/\psi)/(1-\gamma)} \right)^{1/(1-1/\psi))}, \tag{11}$$

where C_t is final consumption, γ is the coefficient of relative risk aversion, and ψ is the intertemporal elasticity of substitution (IES). Consumption is a composite of goods produced in all sectors,

$$C_t = \prod_{s=1}^{S} (\xi^s)^{-\xi^s} (c_t^s)^{\xi^s}, \tag{12}$$

where c_t^s is consumption of good s and $\xi^s \geqslant 0$ are weights that satisfy $\sum_{s=1}^{S} \xi^s = 1$. The household supplies its time endowment in a competitive labor market in every period. For convenience, the time endowment is normalized to 1. Labor is completely mobile between sectors.

The financial assets in this economy are shares and one-period bonds, both of which can be traded costlessly. Shares are claims on the profits made by the firms in each sector and are bundled into a mutual fund for that sector. Bonds are riskless in the sense that they pay one unit of consumption at maturity regardless of the state of nature. The household's budget constraint is

$$\sum_{s=1}^{S} p_t^s c_t^s + q_t^b b_t + \sum_{s=1}^{S} q_t^s a_t^s = \sum_{s=1}^{S} w_t^s n_t^s + b_{t-1} + \sum_{s=1}^{S} (d_t^s + q_t^s) a_{t-1}^s, \tag{13}$$

where q_t^b is the price of a bond, b_t is the number of bonds, and q_t^s and a_t^s are respectively the price of a share and the number of shares of the mutual fund of sector s. The aggregate price index is

$$P_t = \prod_{s=1}^{S} (p_t^s)^{\xi^s}. \tag{14}$$

The aggregate price index serves as the numeraire in this model and, hence, $P_t = 1$ for all t.

The final consumption of the good produced in sector s is the solution to

$$\max_{\{c_t^s\}} \prod_{s=1}^{S} (\xi^s)^{-\xi^s} (c_t^s)^{\xi^s}, \tag{15}$$

subject to the constraint that $\sum_{s=1}^{S} p_t^s c_t^s$ equals a given expenditure level. The solution is

$$c_t^s = \xi^s C_t / p_t^s, \tag{16}$$

which implies $\sum_{s=1}^{S} p_t^s c_t^s = C_t$. Since ξ^s varies across sectors, expenditure shares will vary across sectors as well. The assumption of a Cobb-Douglas aggregator in (12) implies that the expenditure share of goods produced in sector s in total consumption is equal to the weight ξ^s.

2.3 Asset Pricing

The Euler equations that describe the household's utility maximization are

$$q_t^b = \beta E_t\left(\Lambda_{t,t+1}\right), \tag{17}$$

$$q_t^s = \beta E_t\left(\Lambda_{t,t+1}(d_{t+1}^s + q_{t+1}^s)\right), \tag{18}$$

for $s = 1, 2, \ldots, S$, where

$$\Lambda_{t,t+1} = \left(V_{t+1}/W_t\right)^{1/\psi-\gamma}\left(C_{t+1}/C_t\right)^{-1/\psi}, \tag{19}$$

$V_t \equiv \max U_t$ is the value function, and $W_t \equiv E_t V_{t+1}$ is the certainty-equivalent future utility. As usual, Euler equations compare the marginal cost of acquiring an additional unit of the financial asset (thus, sacrificing some current consumption) with the discounted expected marginal benefit of keeping the asset until next period.

Define the gross return on shares of sector s as $r_{t+1}^s = (d_{t+1}^s + q_{t+1}^s)/q_t^s$ and rewrite equation (18) as

$$1 = E_t\left(\beta\Lambda_{t,t+1}\right)E_t(r_{t+1}^s) + R_t^s \tag{20}$$

where

$$R_t^s = cov_t\left(\beta\Lambda_{t,t+1}, r_{t+1}^s\right) \tag{21}$$

is the risk premium. Then, using equation (17) and defining the gross yield of the riskless bond as $r_{t+1}^b = 1/q_t^b$, equation (20) can be written as

$$E_t(r_{t+1}^s) - r_{t+1}^b = -r_{t+1}^b R_t^s, \tag{22}$$

where the left-hand side is the excess return of the shares of sector s. Equation (22) has the usual implication that the excess return is positive when the return, r_{t+1}^s, is negatively correlated with the pricing kernel, $\beta\Lambda_{t,t+1}$, which means that the return is high when consumption is high. More importantly, the risk premium and excess return vary systematically across sectors because sectoral returns covary in a quantitatively different way with the pricing kernel.

2.4 Shocks

The sector-specific shock is a total-factor productivity (TFP) shock that follows the process

$$\ln z_t^s = \rho_s \ln z_{t-1}^s + \epsilon_{s,t}, \tag{23}$$

where $\rho_s \in (-1, 1)$ is the autocorrelation coefficient and $\epsilon_{s,t}$ is an independent and identically distributed (i.i.d.) innovation with mean zero and variance $\sigma_{\epsilon_s}^2$. Notice that the persistence and variance of this productivity shock varies across sectors. The aggregate shock is a labor-augmenting productivity shock that follows the process

$$\ln z_t = \varsigma + \ln z_{t-1} + \epsilon_t, \tag{24}$$

where the drift ς determines the gross rate of growth of the economy and ϵ_t is an i.i.d. innovation with mean zero and variance σ_ϵ^2. This shock specification is attractive because 1) it helps capture the high persistence in the data, 2) it permits the identification of the aggregate shock, and 3) it delivers a balanced-growth path where all variables grow at a constant rate while allowing heterogeneity in sectoral shocks. Because labor productivity is non-stationary and there is long-run growth in this economy, the model will be rendered stationary by rescaling all variables by z_{t-1}.

2.5 Aggregate Resource Constraint

Using the facts that share holdings in each sector add up to 1, that net bond holdings are zero (because agents are identical), and that wages are the same in all sectors (because labor is completely mobile across sectors), the aggregate counterpart of the household's budget constraint is

$$\sum_{s=1}^{S} p_t^s c_t^s = w_t + \sum_{s=1}^{S} d_t^s, \tag{25}$$

Write profits in sector s as

$$d_t^s = Y_t^s - w_t n_t^s - Q_t^{X^s} X_t^s - \Gamma_t^s Q_t^{X^s},$$

where

$$Y_t^s = p_t^s \left(c_t^s + \sum_{s=1}^{S} x_{s,t}^i + \sum_{i=1}^{S} m_{s,t}^i \right) - \sum_{i=1}^{S} p_t^i m_{i,t}^s \tag{26}$$

is the value added in sector s (i.e., gross output minus the cost of materials inputs). Then, aggregate profits are

$$\sum_{s=1}^{S} d_t^s = \sum_{s=1}^{S} Y_t^s - w_t - \sum_{s=1}^{S} Q_t^{X^s} X_t^s - \sum_{s=1}^{S} \Gamma_t^s Q_t^{X^s}, \tag{27}$$

where I have used the assumption that the total time endowment is equal to 1. Substituting (27) into (25) and rearranging yields

$$C_t + \sum_{s=1}^{S} Q_t^{X^s} X_t^s + \sum_{s=1}^{S} \Gamma_t^s Q_t^{X^s} = \sum_{s=1}^{S} Y_t^s. \tag{28}$$

Equation (28) is the aggregate resource constraint whereby the sum of aggregate consumption and aggregate investment (including adjustment costs) equals aggregate output measured in terms of value added.

2.6 Solution Method

Since this model does not have an exact analytical solution, I use a perturbation method to compute an approximate nonlinear solution. Perturbation methods consist of 1) the exact solution to a simplified form of the original problem and 2) a power series that characterizes deviations from the exact solution.[3] In this paper, the exact solution are the allocations and prices in the deterministic steady state of the model and the power series is the second-order expansion of the policy functions around the steady state (see Jin and Judd, 2002, and Schmitt-Grohé and Uribe, 2004). This perturbation method is computationally faster than projection methods like value function iteration and it performs as well in terms of Euler equation accuracy (see Caldara et al., 2012). The former is an important advantage for this project because, as discussed below in section 3.5, the econometric estimation of the model requires solving the model in each iteration of an optimization routine.

The approximate solution consists of linear and quadratic terms in the state variables and a constant risk-adjustment factor. The state variables are the capital stocks in all sectors, the sector-specific productivity shocks, and the aggregate productivity shock. The risk-adjustment factor is a linear combination of the variances of the shock innovations (see Andreasen, 2012). I exploit this result in section 4.5 to quantify the relative contribution of each shock to the equity premium in each sector.

Finally, I relate the perturbation method to the solution method that involves assuming that the arguments inside the expectations operator in the Euler equations are jointly lognormal and conditionally homoskedastic. The latter method delivers a linear asset pricing function with a constant risk-adjustment factor that is proportional to the variance of consumption (see, among others, Hansen and Singleton, 1983, Campbell, 1996, and Jerman, 1998). The perturbation method does not require the auxiliary assumption of lognormality and its focus is on the policy functions that solve the full dynamic model rather than on the Euler equations alone. In addition, the asset pricing function is nonlinear and the risk-adjustment factor depends on the variance of the innovations to structural shocks, rather than on the variance of consumption.

3. Estimation

This section describes the data and the econometric strategy used to estimate the model, and report the parameter estimates.

[3] For an introduction to perturbation methods in economics see Judd (1998).

3.1 Data

The data used to estimate the model are quarterly observations of the growth rate of consumption, the growth rate of investment, the real return on 3-month Treasury bills (T-bills), and real returns on stocks of three broad sectors on the U.S. economy, namely the primary sector (which produces raw materials), manufacturing, and services. The sample period is from 1966Q1 to 2015Q4. The sample starts in 1966 because before that date there are missing observations in the data for stock returns in raw materials. The sample ends with the latest available observations at the time the data was collected.

Consumption is measured by personal consumption expenditures and investment is measured by private nonresidential fixed investment. The raw data are seasonally-adjusted and reported at the annual rate. The series are converted into real per-capita terms at the quarterly rate dividing by four, by the seasonally-adjusted consumer price index (CPI), and by civilian non-institutional population. The CPI and population are the average of the three monthly observations in each quarter. The 3-month Treasury bill serves as empirical counterpart of the one-period bond in the model and its real return is computed as the ratio of the nominal return on the bill and the CPI inflation rate, both measured in gross quarterly terms. The data were taken from the website of the Federal Reserve Bank of St. Louis (www.stlouisfed.org).

The data on stock returns by industry are constructed by Kenneth French using raw data from the Center for Research in Security Prices (www.crsp.com).[4] Each NYSE, AMEX, and NASDAQ stock is assigned to an industry portfolio at the end of June of each year depending on its four-digit Standard Industrial Classification (SIC) code at that time. Equally-weighted returns on industry portfolios are available at several level of disaggregation, but it easy to aggregate up to the three industries used in this project as follows: the primary sectors is SIC codes 0100 to 1499, which include agriculture, mining, and oil and gas extraction; manufacturing is SIC codes 1500 to 3999, which includes construction and durable and nondurable manufacturing; and services is SIC codes 4000 to 8999, which include transportation, communications, utilities, trade, and finance.[5] The raw returns in the database are monthly and I compute the quarterly returns as the product of the three gross monthly returns of each quarter.

Table 1 reports descriptive statistics of the data used to estimate the model. The rates used to compute these statistics are annual and expressed as a percent. The average real return of the 3-month T-bill over the sample period is only about 0.80 percent per year and the standard

[4] These data are available at http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/index.html

[5] In preliminary work, I also estimated the model using value-weighted returns. Results are very similar to those reported here and support the same conclusions.

deviation is relatively low, 2.74 percent. The average return of stocks is much higher than that of T-bills, but there are differences across sectors: the average return of industry portfolios for the primary sector, manufacturing, and services are 4.36, 7.54, and 7.26 percent, respectively, while their standard deviations are 63.46, 54.60, and 46.98, respectively. Thus, the return of stocks in firms that produce raw materials is generally lower and more volatile than that of firms that produce manufactured goods and services. Finally, the standard deviation of consumption growth is relatively low (3.04) compared with investment growth (7.96) and stock returns.

3.2 Production Function Parameters

The parameters of the production functions in the three sectors are estimated using the sectoral input-output database (KLEM) constructed by Dale Jorgenson and described in Jorgenson and Stiroh (2000).[6] The database contain quantities and producer prices of total output, capital services, labor inputs, and material inputs for U.S. sectors disaggregated at the two-digit level of the SIC for the period 1960 to 2005. Aggregation up to the three sectors used here is consistent with the one for stock returns. Thus, the primary sector is SIC codes 1 to 14, manufacturing is SIC codes 15 to 39, and services is SIC codes 40 to 89. The first-order conditions that describe the optimal choice of labor and materials imply

$$\eta^s = w_t^s n_t^s / P_t y_t^s, \tag{29}$$

$$\theta^s = Q_t^{M^s} M_t^s / P_t y_t^s, \tag{30}$$

where $Q_t^{M^s} M_t^s = \sum_{i=1}^{S} p_t^i m_{i,t}^s$. Aggregating the KLEM data as described above allows me to compute the wage bill, total expenditures on materials, and the value of total output for each of the three sectors for each year in the sample. In turn, the ratios (29) and (30) deliver estimates of η^s and θ^s for each sector and year of the sample, with α^s computed as $1 - \eta^s - \theta^s$ because the production function is constant returns to scale. The final estimates of η^s, θ^s, and α^s are the sample averages of the yearly estimates and their standard deviations are $\sqrt{\sigma^2/T}$ where $T = 46$ is the sample size and σ^2 is the variance of the yearly observations. The estimates are reported in table 2. Three observations follow from table 2. First, the primary sector and manufacturing are intensive in materials inputs, while services is intensive in labor. Second, the production function parameter are quantitatively and statistically different across sectors. Finally, materials inputs are a large share of productive inputs in all sectors and, thus, network interactions are likely to be important for the pricing of sectoral shares.

[6] The data are available at http://scholar.harvard.edu/jorgenson/data.

3.3 Consumption Weights

The estimation of the consumption weights uses the implication of the Cobb-Douglas aggregator (12) that the optimal expenditure share on goods from each sector is constant and equal to ξ_s. I estimate these shares using the data from the column "Personal Consumption Expenditures" in the final-user part of the 1992 Use table of the Input-Output (I-O) accounts.[7] Producing sectors are aggregated up to the 3 sectors examined here and the shares are computed as the ratio of the purchases by consumers of commodities from sector s over total consumption expenditures. By construction, $\xi_s \in [0,1]$ and $\sum_{s=1}^{S} \xi_s = 1$ for all s. These shares are reported in the first column of table 2 and show that final consumption consists mostly of services (79.2 percent) and manufactured goods (20.1 percent), and that (not surprisingly) households consume limited quantities of raw materials directly. This means that the key interaction in the final goods market is that between services and manufacturing.

3.4 Materials and Investment-Goods Weights

The optimal choice of materials inputs and investment goods in equations (9) and (10) imply that the expenditure share on goods purchased from sector i is constant and equal to the weights ζ_{is} and κ_{is}, respectively. Thus, I estimate these weights using expenditures shares computed using data from the I-O accounts as follows.

For the materials inputs weights ζ_{is} the raw data come from the 1992 Use table of the I-O accounts. This table reports the total use of commodities by intermediate users in producer prices, with rows containing commodities and columns containing users. The table is produced at different levels of disaggregation but it is easy to aggregate up to the 3 sectors studied here. I compute the expenditure shares as the ratio of the purchases by sector s of commodities from sector i over the total purchases by sector s. By construction, $\zeta_{is} \in [0,1]$ and $\sum_{i=1}^{S} \zeta_{is} = 1$ for all s. The fact that purchases are in producer prices is consistent with the model, where there are no taxes and, hence, consumer and producer prices coincide.

I equate commodities with sectors as in the model, where good s is produced only by sector s. This amounts to assuming that the Make table of the I-O accounts is diagonal and permits the estimation of the weights ζ_{is} employing the Use table alone. The Make table reports the value of each commodity produced by each industry and, in practice, it is not diagonal because there are

[7] I use the 1992 tables because they are roughly in the middle of the sample and, thus, capture the average interaction between sectors during the period. To evaluate whether result may depend on the tables used, I performed the same calculations described in sections 3.3 and 3.4 using the tables for 1982. However, results are very similar because the expenditure shares are relatively stable at the level of disaggregating that I consider here.

commodities that are physically produced by one sector but classified under another sector in the I-O accounts. For instance, I-O accounts treat printed advertisement as a service even though it is produced by printing and publishing, which is part of manufacturing. I examined the quantitative importance of the off-diagonal terms by computing the share of each commodity that is produced in each sector. Since the diagonal elements are all above 0.99, I conclude that treating the Make table as diagonal is a reasonable approximation at this level of disaggregation. The weights (shares) ζ_{is} computed using the Use table are reported in table 3 and show that, at this level of disaggregation, all sectors use materials from all sectors, as in the round-about structure assumed in the model.

For the investment goods weights κ_{is}, the raw data come from 1992 capital flow table (CFT). The CFT is a matrix with 163 commodities (rows) and 64 purchasing industries (columns). The 163 commodities (equipment and structures) are classified by commodity number, but it is trivial to match the commodity number with the SIC code of the producing industry. The 64 purchasing industries are classified by SIC code. The entries in the table are total flows in producer prices. I compute the expenditure shares as the ratio of the purchases by sector s of equipment and structures from sector i over the total purchases by sector s. By construction, $\kappa_{is} \in [0, 1]$ and $\sum_{i=1}^{S} \kappa_{is} = 1$ for all s. The weights (shares) are reported in table 4 and show that most of the U.S. capital stock is produced in the manufacturing sector, which here includes construction and durable manufacturing. The fact that the primary sector produces some of its own capital reflects the fact that oil and gas extraction (SIC code 13) produces a substantial part of its own capital stock. The small, but non-negligible, proportion of investment goods produced in the services sector is due to the fact that this sector includes services that are ancillary to investment (e.g., engineering services).

3.5 Simulated Method of Moments

The remaining parameters of the model are estimated by the simulated method of moments (SMM). Define by $\theta \in \Theta$ the $q \times 1$ vector of structural parameters. The SMM estimator is

$$\widehat{\theta} = \arg\min_{\{\theta\}} \left((1/T) \sum_{t=1}^{T} m_t - (1/\lambda T) \sum_{\iota=1}^{\lambda T} m_\iota(\theta) \right)' \mathbf{W} \left((1/T) \sum_{t=1}^{T} m_t - (1/\lambda T) \sum_{\iota=1}^{\lambda T} m_\iota(\theta) \right), \quad (31)$$

where $\mathbf{W}$ is a $q \times q$ weighting matrix, T is the sample size, λ is a positive integer, m_t is a $p \times 1$ vector of empirical observations on variables whose moments are of interest to us, and $m_\iota(\theta)$ is a counterpart of m_t with elements obtained from the simulation of the model. In words, the SMM estimator minimizes the weighted distance between the unconditional moments predicted by the model and those computed from the data, where the moments predicted by the model are obtained using artificial data simulated from the model. Lee and Ingram (1991) and Duffie and Singleton (1993) show that the SMM estimator is consistent and asymptotically normal with distribution

$$\sqrt{T}(\widehat{\theta}-\theta) \rightarrow N(\mathbf{0},(1+1/\lambda)(\mathbf{J}'\mathbf{W}^{-1}\mathbf{J})^{-1}\mathbf{J}'\mathbf{W}^{-1}\mathbf{\Sigma}\mathbf{W}^{-1}\mathbf{J}(\mathbf{J}'\mathbf{W}^{-1}\mathbf{J})^{-1}), \tag{32}$$

where

$$\mathbf{\Sigma} = \lim_{T\rightarrow\infty} Var\left((1/\sqrt{T})\sum_{t=1}^{T}\mathbf{m}_t\right) \tag{33}$$

and $\mathbf{J} = E(\partial m_\iota(\theta)/\partial\theta)$ is a finite Jacobian matrix of dimension $p \times q$ and full column rank. Estimation is computationally demanding because the model needs to be solved in each iteration of the minimization routine that solves (31). An additional computational cost arises from the fact the deterministic steady state depends nontrivially on the some of the model parameters contained in θ (e.g., the intertemporal elasticity of substitution) and, thus, the system of nonlinear equations that determines prices and allocations in steady state needs to be solved in each iteration of the minimization routine as well.

In this project, the weighting matrix is the identity matrix, the matrix Σ is computed using the Newey-West estimator with a Bartlett kernel and bandwidth given by the integer of $4(T/100)^{2/9}$, where $T = 200$ is the sample size, and the matrix $\mathbf{J}$ is computed by taking numerical derivatives with respect the elements of θ at the optimum. The number of simulated observations is 20 times larger than the sample size (that is, $\lambda = 20$). To limit the effect of starting values on the results, the simulated sample contains 5000 additional "training" observations that are discarded for the purpose of computing the moments. The dynamic simulations of the nonlinear model are based on the pruned version of the solution. In particular, I use here the pruning scheme proposed by Andreasen et al. (2017). The moments used to estimate the model are the means, variances, covariances, and the first- and second-order autocovariances of all six series—consumption growth, investment growth and the real return on 3-month T-bills and stock portfolios in raw materials, manufacturing, and services—. Thus, the total number of moments is 39.

The estimated parameters are the intertemporal elasticity of substitution (ψ), the coefficient of risk aversion (γ), the capital-adjustment cost parameter in all sectors (χ^s), the autoregressive coefficient of productivity in all sectors, and the standard deviation of the aggregate and sectoral productivity innovations. Thus, the total number of estimated parameters is 12. During the estimation procedure the discount factor is fixed to 0.997; the depreciation rate is fixed to 0.025 (that is, 10% per year); the gross rate of aggregate productivity growth is fixed to 1.003 (that is, 1.2% per year); and the consumption weights, materials weights, investment-goods weights, and production function parameters are fixed to the estimates reported in tables 2 through 4.

To examine the role of network effects in asset pricing, I also estimate a (counterfactual) version of the model where sectors use only their own good as material and investment good and, consequently, the Input-Output matrix and the Capital Flow table are identity matrices. In this case there are no network effects on production because sectors do not interact with each in the market for intermediate goods (whether materials or investment goods). However, sectors still interact indirectly in the market for final goods because the consumption bundle consumed by households is a composite of goods produced in all sectors.

The local identification of the model parameters requires that $rank(E(\partial m_\iota(\theta)/\partial\theta)) = q$, where θ is the point in the parameter space Θ where the rank condition is evaluated. I verified that this rank condition is indeed satisfied at the optimum $\widehat{\theta}$ for both versions of the model.

3.6 Parameter Estimates

Estimates of the parameters of the two versions of the model are reported in table 2, along with standard deviations computed using a parametric bootstrap with 99 replications.[8] Note that, except for the standard deviation of productivity shock to raw materials, estimates are similar for both versions of the model.

The estimates of the intertemporal elasticity of substitution (IES) are 0.125 and 0.109 for the versions with and without network effects, respectively. Both estimates are statistically different from zero and one. These estimates are quantitatively similar to values reported in earlier literature. For instance, Epstein and Zin (1991) reports values between 0.18 and 0.87 depending on the measure of consumption and on the set of instruments used to estimate the model, and Vissing-Jørgensen (2002) reports values between 0.30 and 1 depending on the households' asset holdings. Havranek (2015) performs the meta-analysis of 169 studies that estimate this parameter and concludes that the IES for asset holders is around 0.35. The risk aversion parameter is relatively large: 9.57 and 15.05 for the versions with and without network effects, respectively. In both cases the estimate is statistically different from zero. There is substantial variation across sectors in the estimate of the capital adjustment cost parameter with the estimate for manufacturing much larger than that of the other two sectors.

The persistence of productivity shocks is high and similar across sectors and versions of the model. For the model with network effects, there is a large difference between the standard deviation of productivity innovations in the primary sector, the standard deviation of productivity innovations in the other two sectors (manufacturing and services), and the standard deviation of aggregate

[8] I use bootstrap rather than asymptotic standard errors because Monte-Carlo results in Ruge-Murcia (2012) indicate that the latter are not always a good approximation to the actual variability of SMM estimates of nonlinear models in small samples.

productivity innovations. In particular, the standard deviation of productivity innovations in the primary sector (0.177) is one order of magnitude larger than in manufacturing and services (0.025 and 0.010, respectively), which in turn are one order of magnitude larger than the standard deviation of aggregate productivity innovations (0.0027). In contrast, for the model without network effects, all sectoral productivity shocks are of the same order of magnitude. As we will see below, the heterogeneity in the volatility of productivity innovations is important in explaining the different predictions of the models with and without network effects.

4. Results

This section examines the time-series implications of the model. In particular, it examines the effects of sectoral shocks on real and financial variables at the sectoral and aggregate levels, and it quantifies the relative contribution of all shocks to the equity risk premia. This section also shows that the nonlinear model with network effects generates conditional heteroskedasticity endogenously.

4.1 Ergodic Distributions

Table 6 reports the means and standard deviations of the ergodic distributions of growth rate of consumption, the growth rate of investment, the real return on 3-month T-bills, and real returns on stocks in the primary, manufacturing, and service sectors implied by the models. The first column reproduces the statistics for the U.S. data that were previously reported in table 1. The models predict similar means of the growth rates of consumption and investment to those observed in the data. Both models predict a mean return for the safe asset that is lower than in the data, but the mean predicted by the model with network effects (0.55) is quantitatively much closer to the value in the data (0.79) than the mean predicted by the model without network effects (0.12).

The models replicate the volatility of stock returns and the fact that volatility is larger for returns in the primary sector than in manufacturing and services. However, the average equity premia predicted by the models is lower than in the data and the difference in mean returns across sectors is also smaller than in the data. This latter result is interesting because it implies that the considerable heterogeneity in the volatility of sectoral shocks (and other features) is diffused through network interactions, which moderates the heterogeneity in stock returns. To see this, notice that both versions of the model match equally well the mean and variances of stock returns, but that the version with network effects does so with a standard deviation of productivity innovations to the primary sector that is almost three times larger than that of the version with network effects (0.177 versus 0.065).

4.2 The Transmission of Shocks Across Sectors

Figures 1 through 3 report the responses of selected sectoral variables to a productivity shock in the primary, manufacturing, and service sectors, respectively. The size of the shock is 1 standard deviation of the respective innovation. Thus, by construction, the shock to the primary sector is larger than the shock to the other two sectors. The shock is assumed to take place when all variables are equal to the mean of their ergodic distribution. In all figures, the vertical axis is the percentage deviation from the ergodic mean and the horizontal axis is periods. The key observation from these figures is that a shock in one sector has effects on the real and financial variables of all sectors through the production network. There are, however, differences in the dynamics as a result of differences in the persistence of the shocks, capital adjustment costs, and the combinations of materials and investment goods used by each sector.

Consider first figure 1, which plots sectoral responses to a productivity shock in the primary sector. The positive productivity shock leads to a large increase in the production of raw materials and a large reduction in its real price. The fact that manufacturing and services are inputs to the production of raw materials means that output in both of these sectors increases as well. The increase in output requires additional labor and capital and, hence, investment rises in all sectors. Since most investment goods are produced in the manufacturing sector (see table 3), the rise in investment in all sectors contributes further to the increase of output in manufacturing. In the end, figure 1 shows that the increase of output in manufacturing is larger than that in services. Part of the reason is that the proportion of expenditures on investment goods that goes into manufacturing is much larger than the proportion that goes into services: 57.5% versus 13.4% (see the first column in table 3). This effect is amplified as the shock propagates through the network. The increase of output in manufacturing is large enough that its real price decreases, while the real price of services increases.[9] The dynamics of investment are different across sectors, in part, because adjustment costs are different across sectors. In particular, investment in manufacturing responds sluggishly to the shock because this sector features large adjustment costs.

Dividends are the return on capital net of investment and of adjustment costs and they increase in all sectors following the positive productivity shock to the primary sector. Share prices increase in all sectors as well. The increase in dividends and share prices are more pronounced in the primary sector than in the other sectors, but the dynamics are heavily influenced by frictions in capital accumulation. To see this, notice that in the primary and service sectors, where adjustment costs are small, investment quickly increases the capital stock and dividends and share prices decrease

[9] Recall that the aggregate price index is the numeraire in this model. Thus, by construction, if one or more real prices decrease, then at least one real price must increase.

monotonically after the initial, positive jump. In contrast, in manufacturing, where adjustment costs are large, the increase in the capital stock takes place slowly and, consequently, the full effect of the shock on dividends and the share price takes place with some delay and the impulse response has a hump shape.

Figure 2 plots sectoral responses to a productivity shock in manufacturing. The positive productivity shock leads to an increase in output in the manufacturing sector and to a decrease in the real price of manufactured goods. Since the primary and service sectors supply materials to manufacturing, their output increases as well, but by less than in manufacturing. The real price of raw materials and services rises, but in the case of raw materials the price overshoots and converges to its ergodic mean from below. In order to increase in output, firms in all sectors must hire additional labor and build up their capital stock and, thus, investment rises in all sector. Since the shock to productivity in manufacturing is less persistent that the shock to the primary sector, the adjustment to the capital stock in figure 2 takes place more rapidly than in figure 1. However, as before, adjustment of capital in manufacturing relative to the other sectors is mores sluggish as a result of high adjustment costs. Interestingly, the increase in the capital stock is larger in services than in manufacturing reflecting both lower adjustment costs and higher capital intensity (see table 2). Dividends increase in all sectors because the value of the marginal return to capital increases after the shock in all sectors, and, consequently, share prices increase as well.

Finally, figure 3 plots sectoral responses to a productivity shock in services. The general pattern uncovered in figures 1 and 2 is present here as well. Thus, output in services increase and the transmission of the shock via the production network induces an increase in output in the other sectors and a generalized increase in the capital stock and investment. The increase in the value of the marginal return to capital leads to increases in dividends and share prices, except in services where the increase in profits is moderated by the fall in the price of services and the relatively large increase in sectoral investment.

4.3 Dynamics of Consumption and Investment

Figure 4 reports the effects on consumption growth, investment growth, the real wage, the bond price, and the bond yield from productivity shocks to the primary sector (column 1), manufacturing (column 2), and services (column 3). As before, the size of the shock is 1 standard deviation of the respective innovation and the shock takes place when all variables are equal to the mean of their ergodic distribution.

All productivity shocks lead to an increase in consumption growth, investment growth, and the real wage. In the case of consumption growth and the real wage the initial effects have roughly similar magnitude despite the fact that shocks have different sizes, but the persistence and shape of the response is different across sectoral shocks. In particular, shocks to the primary sector are more persistent and, since its full effect takes place with some delay, responses are hump shaped. All shocks lead to an increase in investment growth, but the dynamics are different across sectoral shocks. The shocks to the primary sector and manufacturing initially lead to small, negative changes in investment growth. However, investment growth increases over time and after reaching its peak, returns to its ergodic mean from above. In contrast, the shock to services leads to relatively large increase in investment growth, but the effect declines monotonically and is not very persistent.

Regarding the bond price, the initial effects are also different across sectoral shocks. The shock to the primary sector leads to an initially decrease in the bond price and an increase in its yield. Eventually, however, the price (yield) goes above (below) its steady state value and returns that value from above (below). In contrast, the shocks to manufacturing and services lead to an increase in the both price and a decrease in the bond yield, with the variables returning monotonically to their ergodic means. Finally, notice that the effect of the shock to services is quantitatively the largest despite the fact that the shock itself is the smallest. This is partly due to the fact that services are by far the largest component of final consumption (see table 2).

4.4 Comparison with a Model without Network Effects

Figures 5 through 7 plot the responses to sectoral shocks for the model without network effects, where the input-output table and capital flow table are diagonal matrices. Notice that sectors still interact in the final goods markets, but that the proportion of final consumption expenditures of raw materials is small (see table 2). First, compare figure 5 with figure 1 for the productivity shock to the primary sector. The responses of the primary sector to its own shock are qualitatively similar and the quantitative differences are due to the fact that the estimate of the standard deviation of the innovation under the model with no network effects is one-third of the size of the estimate under the model with network effects. However, effects on the other sectors are one or two orders of magnitude smaller. Thus, in the model without network effects, shocks to the primary sectors have limited effects on the other sectors and this is compounded by the fact that households expenditures on raw materials as final goods are limited. A key result from figure 7 is that absent interactions in the market for intermediate inputs, shocks to the primary sector have a small effect on the stock prices and dividends of the other sectors.

Now, compare figure 6 with figure 2 for the productivity shock to manufacturing. The effects on manufacturing are similar in both models, though they are somewhat larger in the model without network effects compared with the model with network effects. Notice that despite the fact that under the former model manufacturing does not use raw materials and services as inputs in productions, the output of these two sectors increase. The reason is simply that all sectors still interact indirectly in the final goods market. As we will see later, aggregate output and consumption increase following the shock to manufacturing and, from the demand functions (see equation (16)), the increase in aggregate consumption is large enough to overcome the negative effect associated with the increase in real prices. Since output increases in all sectors, capital, dividends, and share prices increase in all sectors. Similarly, comparing figures 7 with figure 3 for the productivity shock to services shows that effect on services are similar in both models. The only difference is the fact that dividends increase in the model without network effects because although there is a similar large increase in investment, in this case, by assumption, all services investment are produced by the same sector. As in the previous comparison, the fact that goods form part of final consumption and that aggregate consumption increases means that output in all sectors increase.

Finally, compare figure 4 and 8. The shocks to the primary sector lead to a small increase in aggregate consumption and investment growth and on the real wage compared with the model with network effects and have basically no effect on the bond price because this sector is such a small component of aggregate consumption. In contrast, for the other shocks the qualitative and quantitative effects are very similar because they are large components of final consumption.

In summary results in this section show that without network effects in production and a limited role in final consumption, the primary sector has a limited effect on the real and financial variables in other sectors. Regarding manufacturing and services, results show that, even without network effects in production, the fact that a sector can affect aggregate consumption means that it may have generally a positive effect on the other sectors even if its relative price has increased. This suggests that focusing only on the interaction between sectors at the production stage is potentially restrictive and than their interaction in the final goods market is quantitatively important.

4.5 Composition of the Risk Premia

The equity risk premia in this model is a linear function of the variance of the innovations to the structural shocks. These shocks are an aggregate shock and three sectoral shocks. The aggregate shock hits simultaneously all firms in all sectors, while a sectoral shock hits only the firms in one sector but affects firms in the other sectors via network interactions. In this section, I decompose the contribution of each shock to the risk premia in all sectors for the models with and without network effects. Results are reported in table 7.

First, notice in table 7 that for all sectors and under both models, the contribution of the variance of the aggregate shock to the equity risk premia is small. This result implies that the equity risk premia is primarily driven by sectoral shocks. Standard asset pricing models predict that idiosyncratic risk generates no compensation or risk adjustment. However, in this model sectoral shocks are idiosyncratic only in the narrow the sense that the sectoral shock initially hits only firms in one sector. Thereafter, a sectoral shock effects all sectors because firms interact with each other in the production network. Hence, a sectoral shock contributes to aggregate risk and the risk associated with it is priced by the market.

For the model with network effects, all sectoral shocks make a nontrivial contribution to the equity risk premia in all sectors, with the productivity shock to manufacturing being the largest contributor. In contrast, in the model without network effects the contribution of shocks to the primary sector to the equity risk premia of all sectors is smaller by one or two orders of magnitude than in the model with network effects. This results suggests that risk from the primary sector is transmitted to the other sectors, which are its suppliers and customers, via the production network. The relatively large contribution of the productivity shock to the primary sector to the risk premia in manufacturing and services is remarkable because the primary sector is small: the average contribution of the primary sector to total gross U.S. output during the sample period is only 4.5% (the contribution of this sector to total gross output in the steady state of the model is 4.4%). The outsized contribution of the primary sector to the risk premia in the model with network effects is therefore due to the large volatility of shocks to this sector (see table 5).

Finally, note that even without network effects in production, the interaction in the final goods market implies that both manufacturing and services transmit to each other the risk associated with their sectoral disturbances.

4.6 Endogenous ARCH

Earlier literature documents time-varying volatility in stock returns and estimates specifications based on the autoregressive conditional heteroskedasticity (ARCH) model due to Engle (1982). This section shows that the asset-pricing model endogenously generate ARCH despite the fact that shocks are conditionally homoskedastic. This result is due to the combination of two features of the model: nonlinearity and network effects. The fact that conditionally homoskedastic shocks propagated through a nonlinear system can generate ARCH is well known in the literature (see, for instance, Granger and Machina, 2006). The contribution of this paper is to show that a production network can amplify ARCH effects through network interactions.

Table 8 reports results of Lagrange Multiplier (LM) tests of the hypothesis of no conditional heteroskedasticity (Engle, 1982) applied to the quarterly U.S. data. The test is carried out on the residuals of an autoregression with number of lags selected using the Bayesian information criterion (BIC) and the statistic is calculated as the product of the number of observations and the uncentered R^2 of the ordinary least squares (OLS) regression of squared residuals on a constant and three of its lags. Under the null hypothesis, the statistic is distributed chi-square with three degrees of freedom. The p-values in table 8 show that the hypothesis of no conditional heteroskedasticity can be rejected at the 5% significance level for stock returns in raw materials and consumption growth and at the 10% for stock returns in manufacturing and services, but that it cannot be rejected for bond returns and investment growth.

The table also reports results of tests applied to 1000 artificial observations of series generated from the models with and without network effects. For the version with network effects, the hypothesis of no conditional heteroskedasticity can be rejected at the 5% level for all sectoral stock returns, just as for the U.S. data. In contrast, for the version without network effects the hypothesis can be rejected for stock returns in raw materials, but it cannot be rejected for stock returns in manufacturing and in services (the p-values are 0.78 and 0.99, respectively). For both versions of the model the hypothesis cannot be rejected for bond returns and consumption growth, but it can be rejected for investment growth.

Table 8 also shows that the hypothesis of no conditional heteroskedasticity in excess returns can rejected for all sectors in the U.S. data and in the model with network effects. In contrast, for the version without network effects the hypothesis can be rejected for excess returns in raw materials, but it cannot be rejected for excess returns in manufacturing and services (the p-values are 0.64 and 0.98, respectively).

In summary, results in this section show that this asset-pricing model generates conditional heteroskedasticity endogenously even though shocks are conditionally homoskedastic. Network interactions are important contributors for this result because they allow the transmission of the volatile shocks from the primary sector to the other sectors through the nonlinear model. This accounts for the fact that the hypothesis of no conditional heteroskedasticity can be rejected for stock returns and excess returns in manufacturing and services for the model with network effects, but they cannot be rejected in the model without network effects.

5. Conclusions

This paper constructs a nonlinear asset-pricing model where heterogenous sectors interact with each in a production network. The model is estimated using sectoral U.S. data and results show how sectoral shocks are transmitted through the economy and affect dividends and stock prices. By deliberately focusing on a small network, I am able to construct and estimate a rich model with multiple sources of heterogeneity and to fully characterize its time-series implications. I show that sectoral shocks to the primary sector play an important role in the stock returns of other sectors because, although this sector is small, it is subject to very volatile and persistent shocks. I also show that the nonlinear model endogenously generates conditional heteroskedasticity in stock returns and excess returns despite the fact the shocks are conditionally homoskedastic. The comparison with a model without input-output interactions shows that these two results crucially depend on the existence of a network that allows the transmission of shocks from the primary sector to the other sectors.

Table 1: Descriptive Statistics

Variable	Mean	Standard Deviation
Consumption growth	1.199	3.037
Investment growth	1.081	7.964
3-month T-bill rate	0.788	2.744
Stock returns		
Primary	4.360	63.462
Manufacturing	7.538	54.599
Services	7.259	46.982

Notes: The table reports summary statistics of the data used to estimate the model. The rates of growth (consumption and investment) and returns (stocks and T-bill) are real, annual, and expressed as a percent. The sample consists of 200 quarterly observations between 1966Q1 and 2015Q4.

Table 2. Consumption Shares and Production Function Parameters

	Shares	Production Function Parameters					
		η^s		α^s		θ^s	
Sector	ξ^s	Estimate	s.e.	Estimate	s.e.	Estimate	s.e.
Primary	0.007	0.203*	0.030	0.273*	0.035	0.524*	0.024
Manufacturing	0.201	0.289*	0.011	0.104*	0.015	0.607*	0.012
Services	0.792	0.395*	0.011	0.218*	0.007	0.387*	0.014

Note: The table reports estimates of final consumption shares and production function parameters for each sector. s.e. denotes standard error and $*$ denotes significance at the 5 percent level.

Table 3. Input-Output Matrix

Producer	Consumer Primary	Consumer Manufacturing	Consumer Services
Primary	0.372	0.105	0.034
Manufacturing	0.258	0.575	0.229
Services	0.370	0.320	0.738

Notes: This table reports the share of total expenditures on materials inputs by the consuming sector that goes into goods from the producing sector. The shares were computed by the author using the table "The Use of Commodities by Industries" for 1992 produced by the BLS. Columns may not add up to one due to rounding.

Table 4. Capital Flow Table

	Consumer		
Producer	Primary	Manufacturing	Services
Primary	0.291	0.000	0.000
Manufacturing	0.575	0.843	0.896
Services	0.134	0.157	0.104

Notes: This table reports the share of total expenditures on investment goods by the consuming sector that goes into goods from the producing sector. The shares were computed by the author using the table "Distribution of New Equipment and Structures to Using Industries in Producers' Prices" for 1992 produced by the BLS. Columns may not add up to one due to rounding.

Table 5. SMM Estimates

	Model			
	Network Effects		No Network Effects	
Parameter	Estimate	b.s.e.	Estimate	b.s.e.
Preferences				
Elasticity of substitution	0.1249*	0.0156	0.1086*	0.0126
Risk aversion	9.5659*	1.5457	15.0498*	2.2107
Primary				
Capital adjustment cost	215.6140*	71.1321	100.7815	102.2275
Autoregressive coefficient	0.9987*	0.0019	0.9969*	0.0045
Standard deviation	0.1773*	0.0550	0.0651*	0.0228
Manufacturing				
Capital adjustment cost	1371.5927	4136.9543	1633.0767	3299.7235
Autoregressive coefficient	0.9649*	0.0094	0.9802*	0.1967
Standard deviation	0.0248*	0.0053	0.0286*	0.0057
Services				
Capital adjustment cost	136.8366*	24.3182	260.8285*	47.3991
Autoregressive coefficient	0.9118*	0.0230	0.9365*	0.0117
Standard deviation	0.0101*	0.0015	0.0105*	0.0014
Aggregate Productivity				
Standard deviation	0.0027	0.0046	0.0024	0.0050

Note: The table reports SMM estimates of the model parameters under different network structures, b.s.e. denotes standard errors computed using a parametric bootstrap with 99 replications, and $*$ denotes significance at the 5 percent level.

Table 6: Ergodic Distributions

Variable	Data	Model	
		Network Effects	No Network Effects
Means			
Consumption growth	1.199	1.069	1.211
Investment growth	1.081	1.109	1.213
3-month T-bill rate	0.788	0.551	0.123
Stock returns			
Primary	4.360	1.120	1.359
Manufacturing	7.538	1.125	1.483
Services	7.259	1.210	1.435
Standard Deviation			
Consumption growth	3.037	10.686	8.754
Investment growth	7.964	11.366	6.940
3-month T-bill rate	2.744	9.677	10.227
Stock returns			
Primary	63.462	61.523	63.825
Manufacturing	54.599	51.745	53.213
Services	46.982	43.146	44.286

Notes: The table reports the mean and standard deviation of the U.S. data and of artificial data simulated from the models. The rates of growth (consumption and investment) and returns (stocks and T-bill) are real, quarterly and expressed as a percent.

Table 7. Composition of the Equity Risk Premia (in %)

	Model	
Sector/Shock	Network Effects	No Network Effects
Primary		
Aggregate	0.10	0.13
Primary	33.31	1.86
Manufacturing	39.94	45.20
Services	26.65	52.81
Manufacturing		
Aggregate	0.16	0.19
Primary	16.28	0.04
Manufacturing	52.23	56.74
Services	31.34	43.03
Services		
Aggregate	0.16	0.19
Primary	17.58	0.05
Manufacturing	50.25	45.52
Services	32.01	54.24

Note: The table reports the contribution of each shock to the equity risk premia for the models with and without network effects.

Table 8: Test of No Conditional Heteroskedasticity

	U.S. Data	Model: Network Effects	Model: No Network Effects
Consumption growth	0.002	0.557	0.894
Investment growth	0.239	< 0.001	< 0.001
3-month T-bill rate	0.250	0.311	0.297
Stock returns			
Primary	< 0.001	< 0.001	< 0.001
Manufacturing	0.088	0.013	0.784
Services	0.077	0.035	0.991
Excess returns			
Primary	< 0.001	< 0.001	< 0.001
Manufacturing	0.094	0.012	0.642
Services	0.027	0.026	0.981

Notes: This table reports p-values of Lagrange Multiplier tests of the hypothesis of no conditional heteroskedasticity (Engle, 1982).

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Figure 1: Responses to a Productivity Shock in the Primary Sector with Network Effects

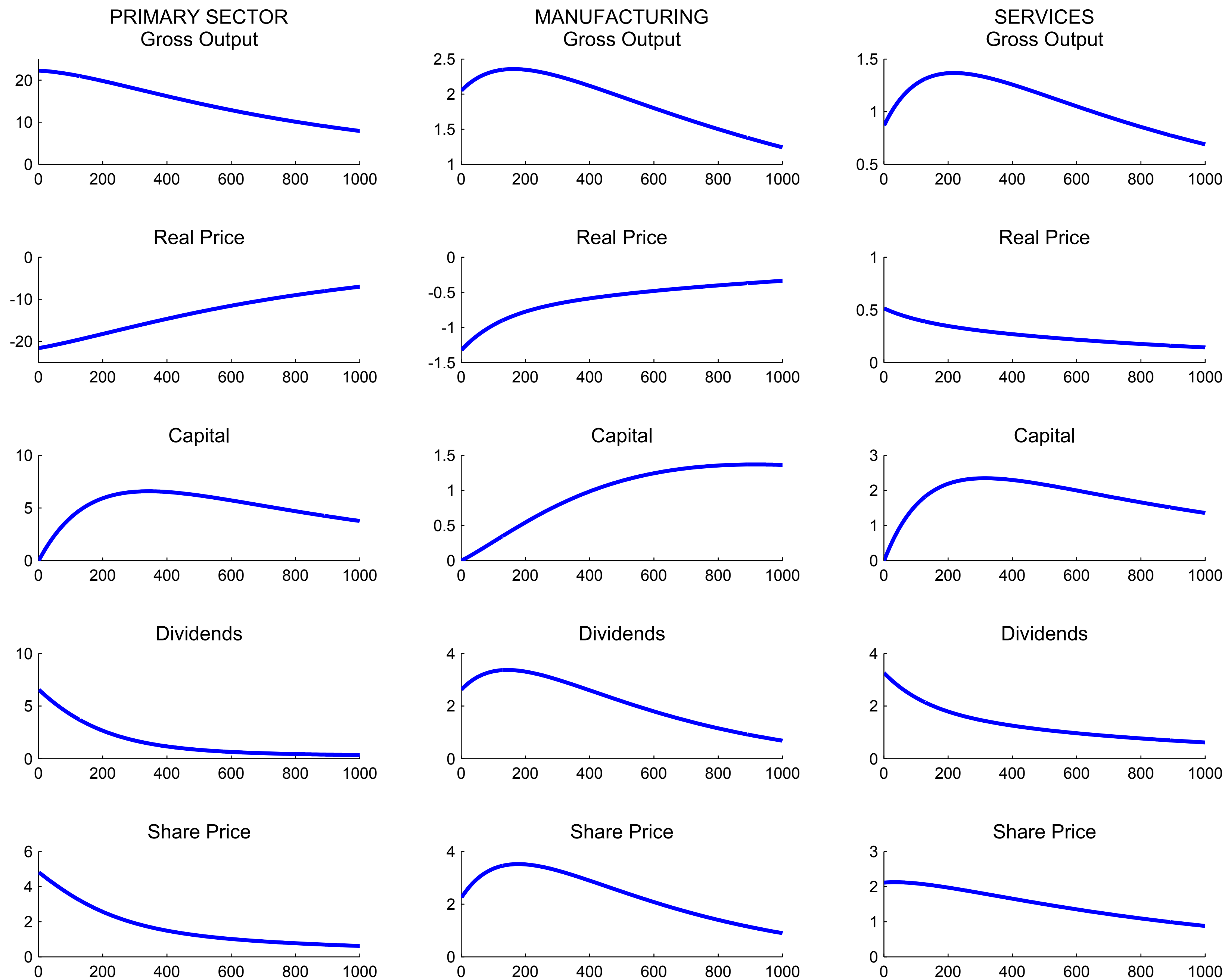


Figure 2: Responses to a Productivity Shock in Manufacturing with Network Effects

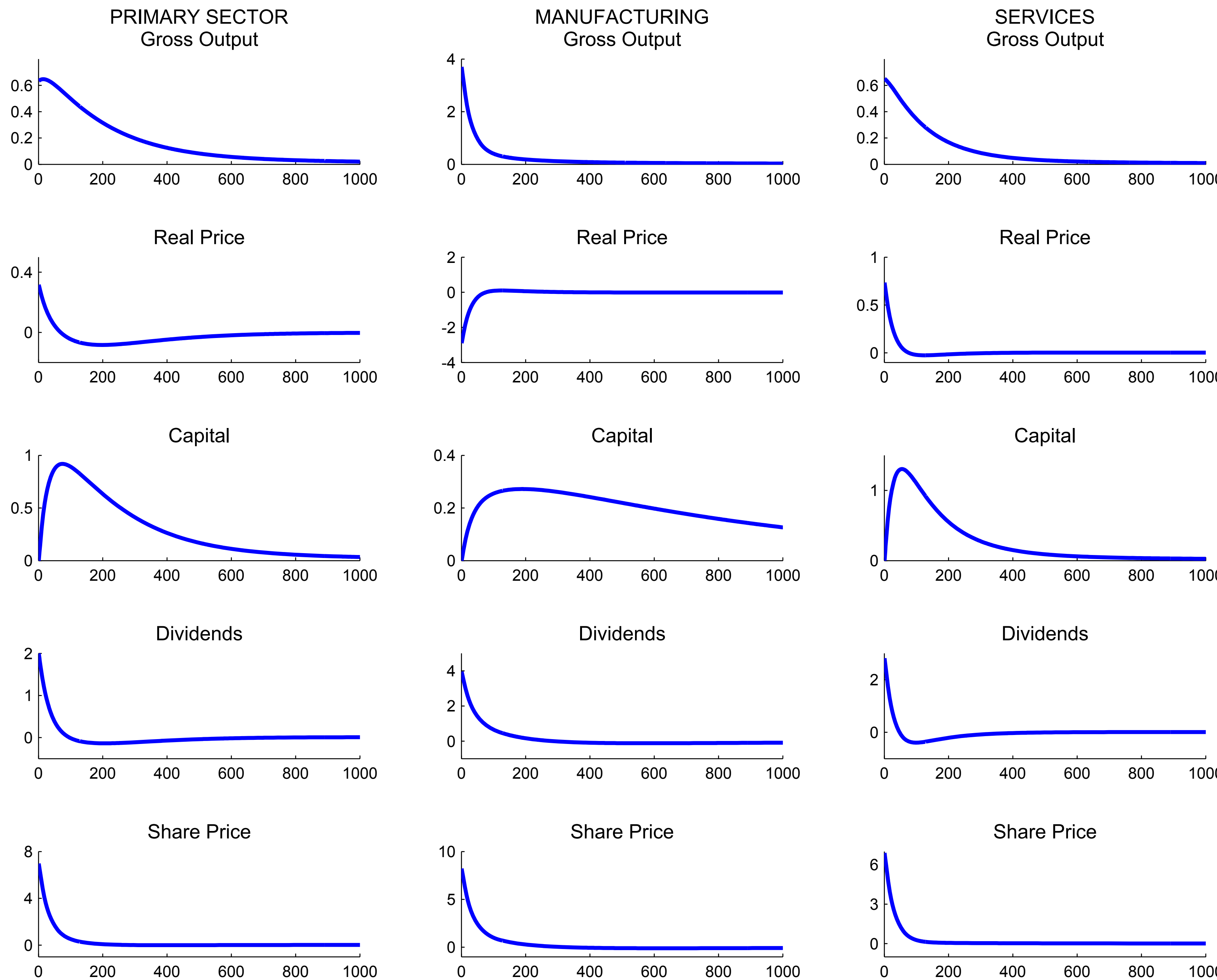


Figure 3: Responses to a Productivity Shock in Services with Network Effects

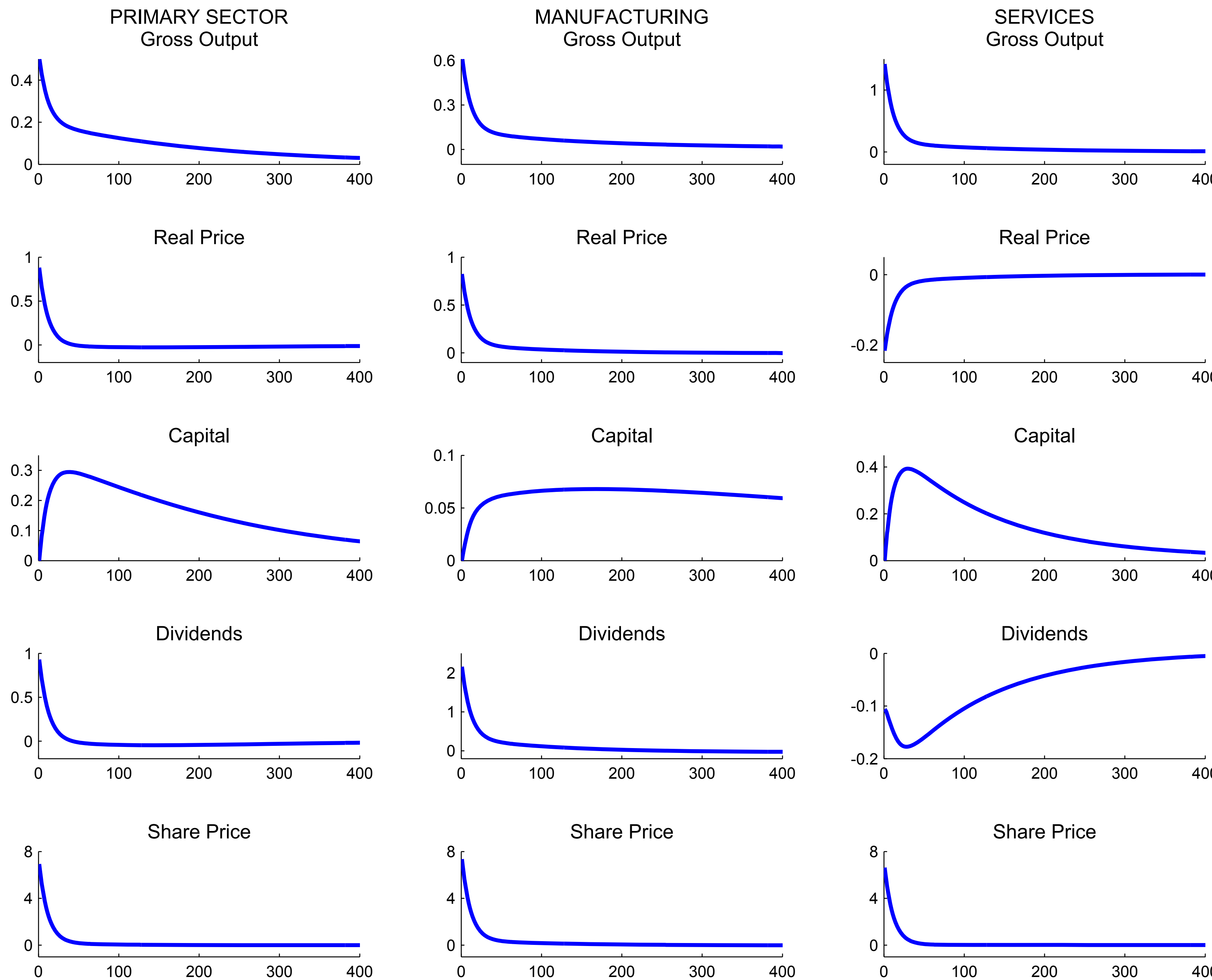


Figure 4: Responses of Aggregate Variables to Sectoral Shocks with Network Effects

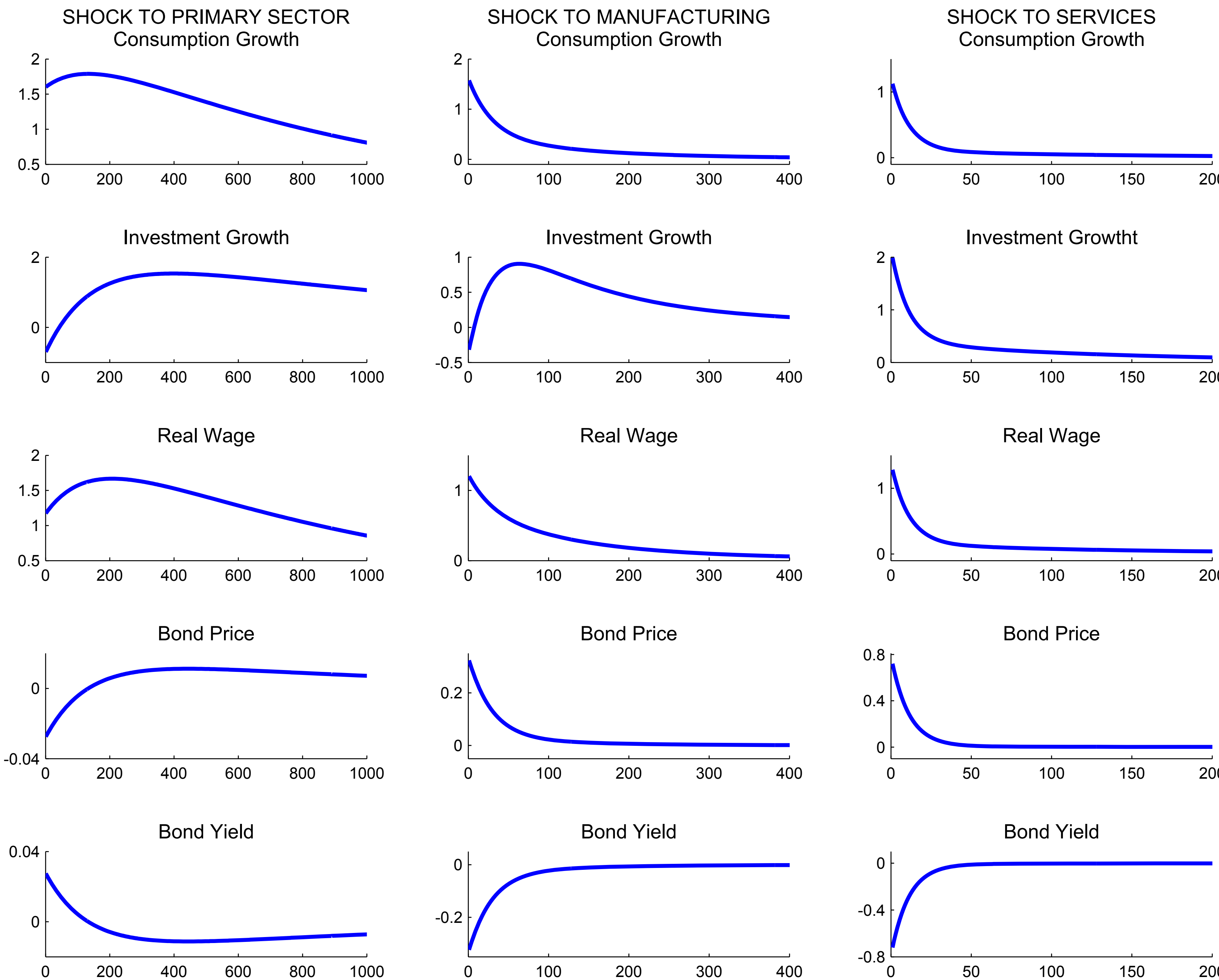


Figure 5: Responses to a Productivity Shock in the Primary Sector without Network Effects

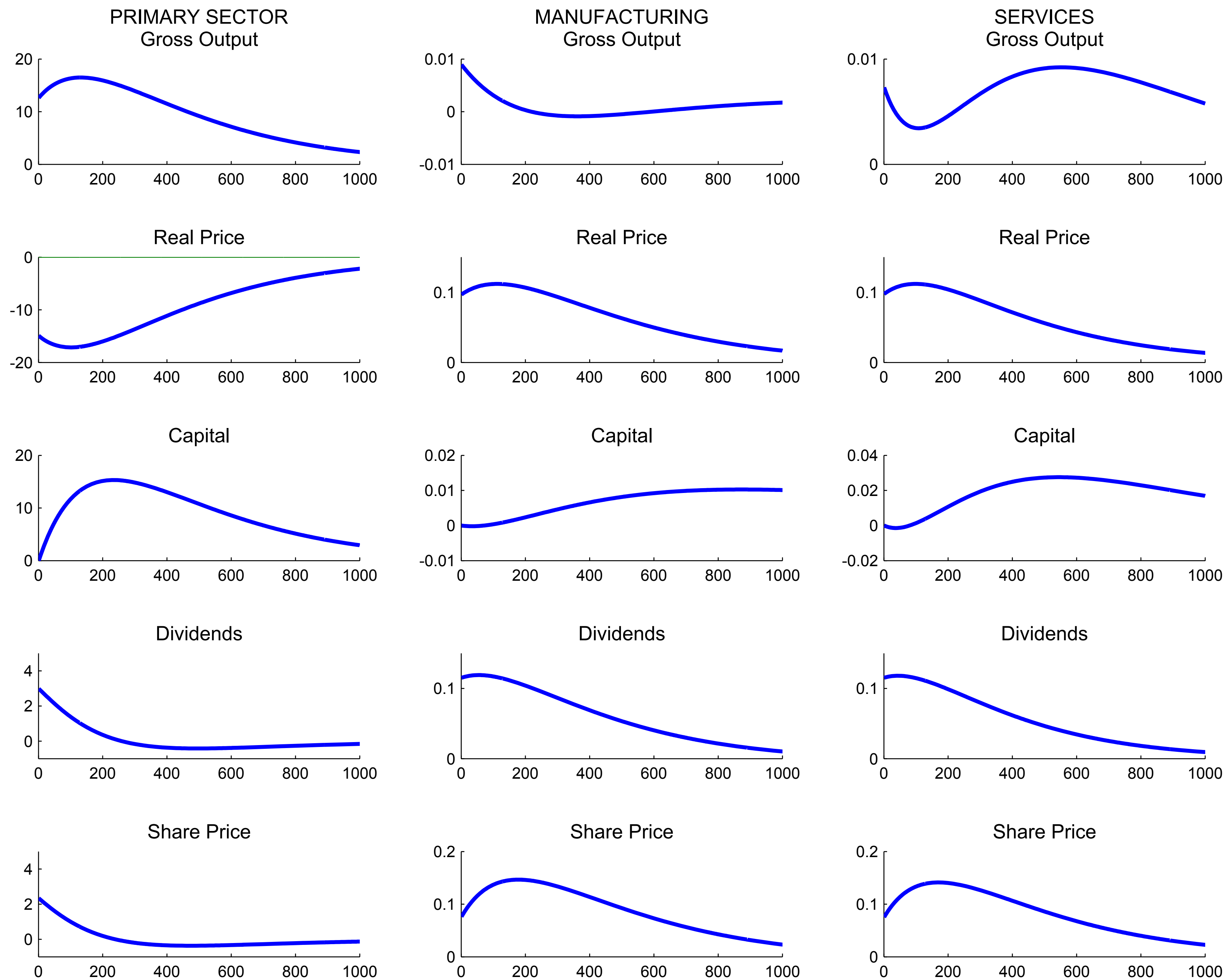


Figure 6: Responses to a Productivity Shock in Manufacturing without Network Effects

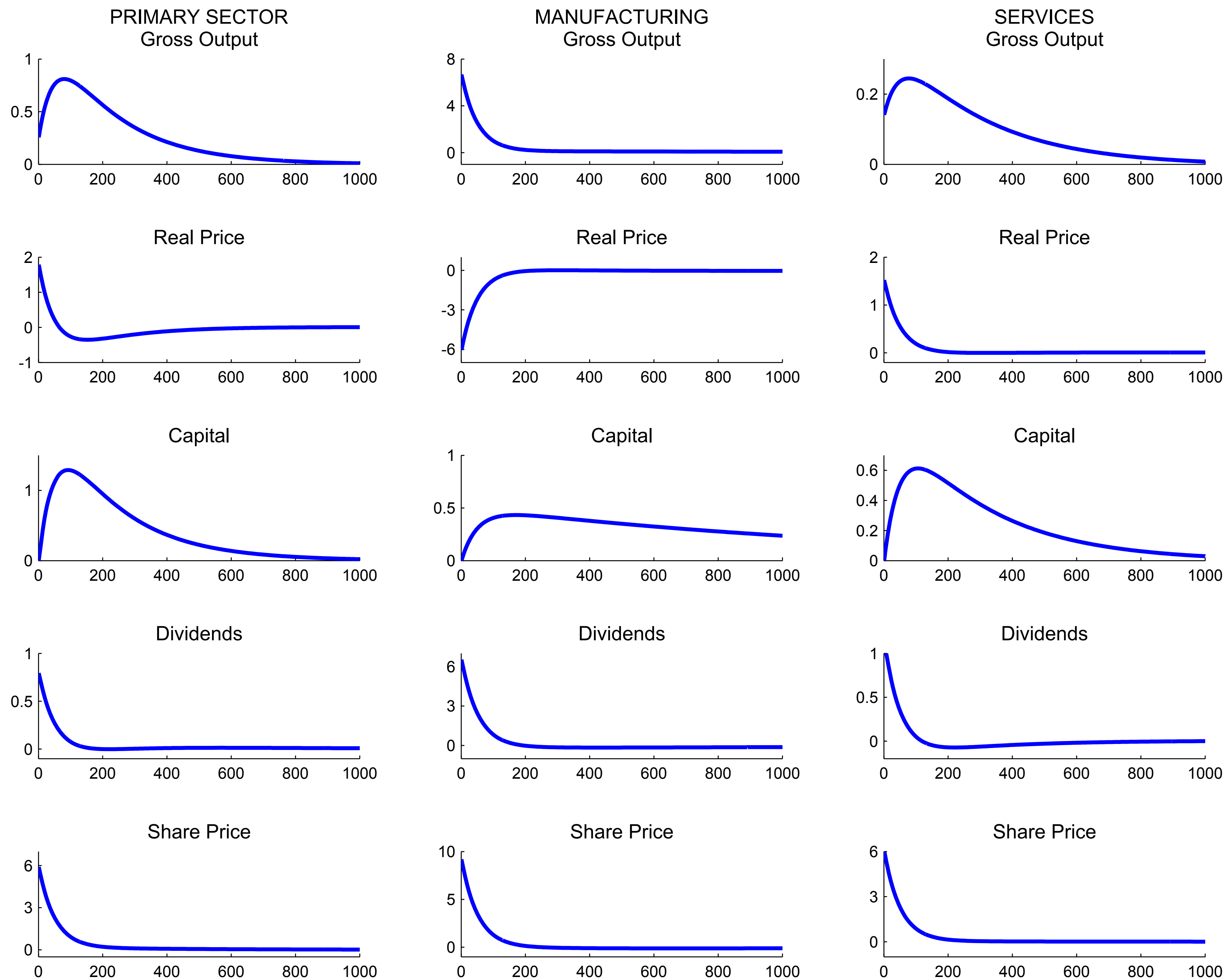


Figure 7: Responses to a Productivity Shock in Services without Network Effects

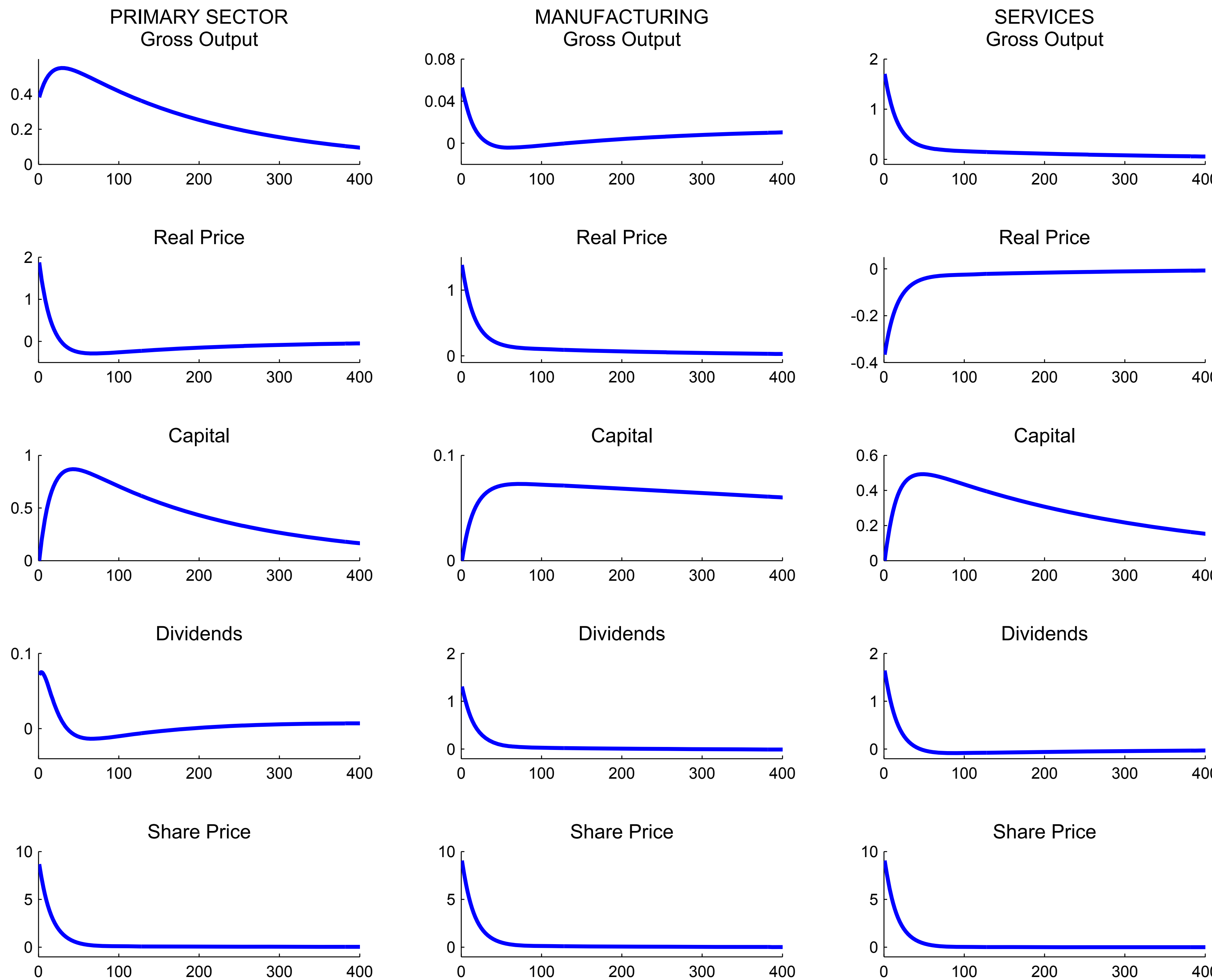
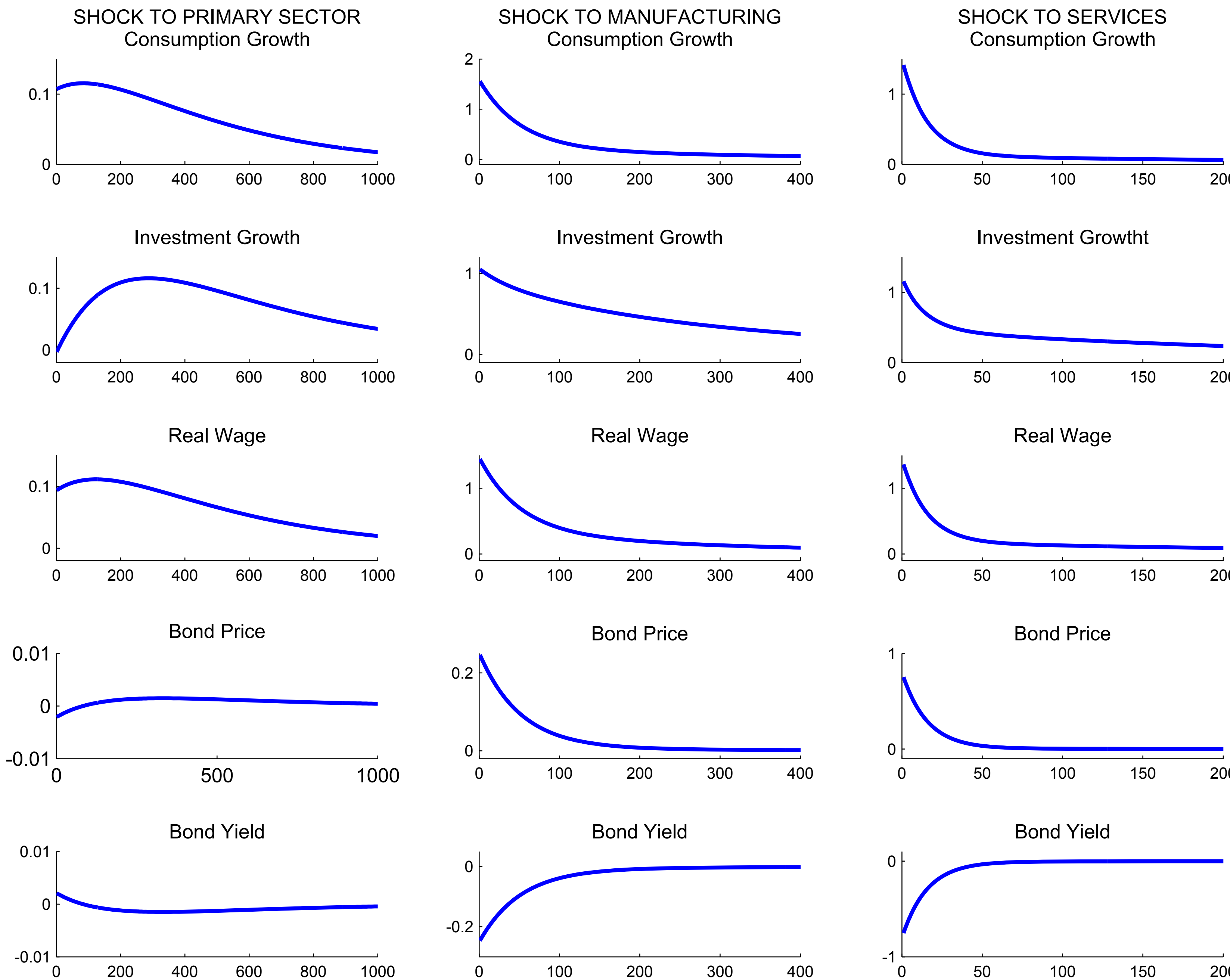


Figure 8: Responses of Aggregate Variables to Sectoral Shocks without Network Effects



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