

*Nonlinear Models of Agricultural Production Efficiency: Bayesian, Classical, and Entropy Perspectives (Robert G. Chambers, University of Maryland, presiding)*

## **AN ANALYSIS OF GRAIN PRODUCTION DECLINE DURING THE EARLY TRANSITION IN UKRAINE: A BAYESIAN INFERENCE**

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The first years of reforms in the former Soviet Union resulted in a sharp decline in agricultural production. Between 1989 and 1992, Ukrainian gross agricultural product dropped some 20%, and the output of grain, which is produced mostly in the collective sector, went down some 25% (World Bank). Several reasons for the fall have been advanced. In addition to weather variation across years, there was a drop in state deliveries of production inputs, especially fertilizer and pesticides (World Bank). The emergence of private opportunities resulted in labor and management migration from the large-scale collective system (Csaki and Lerman), thus reducing the average labor quality in the sector. The ability of farms to produce efficiently was also affected by the transition-related break in old production ties and networks (Blanchard and Kremer). While all three explanations of production differences between years (weather variability, input quantities decline, and loss of production efficiency) are plausible, little is known about the relative contribution of these factors to the overall decline in production. Identifying the reasons for the decline in agricultural output in countries like Ukraine is not

only important from a historical perspective, but furthermore, may be important to anticipate the chances of success of new policies and initiatives, such as accession to the European Union (Macours and Swinnen). We attempt to fill in the gap and improve the understanding of the decline in grain production in early transition Ukraine.

Much of the literature devoted to the analyses of the changes in agricultural production in the former Soviet Union focuses on the later transition years and uses data aggregated both across outputs and farms (e.g., Osborn and Truebold, Sotnikov, Sedik, Truebold, and Arnade). Macours and Swinnen used country-level agricultural production data from several Central and Eastern European countries and found that severe drought and reductions in production factor use accounted for around 10% and 80%, respectively, of total output decline between 1989 and 1995. Kurkalova and Jensen, who used farm-level survey data of Ukrainian farms, estimated that the decline in input quantities and technical efficiency decline contributed about half each to the overall drop of grain production between 1989 and 1992. Neither of the last two studies provided standard errors on the estimates of the shares of the components of output decline. Yet knowing the standard errors is important as underestimating the estimation error may lead to overly optimistic inferences. This paper extends the analysis of Kurkalova and Jensen by (a) focusing specifically on the decomposition of output decline into its components, and (b) explicit modeling of the effect of weather on grain production.

The objective of this study is to quantify the contributions of weather variability, decline

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**Table 1. Summary Statistics for Variables in the Stochastic Frontier Production Model of Grain Production**

Variable	Units	Mean	St. Dev.	Minimum	1st Quartile	Median	3rd Quartile	Maximum
Production	Tons	3,972	2,361	1,219	2,728	3,466	4,356	18,574
Land	Hectares	1,112	517	268	829	970	1,141	2,850
Labor	1,000 hours	32	29	6	17	26	39	219
Fertilizer	100 tons	79	78	14	40	59	86	596
Chemicals	Tons	6.6	3.7	1.6	4.5	5.9	7.5	21.4
Fuel	1,000 liters	93	51	24	66	79	92	285
Ratio of nonagricultural to total workers	Number	0.143	0.053	0.041	0.107	0.136	0.169	0.317
Agricultural workers per agricultural land	Number per hectare	0.141	0.031	0.081	0.119	0.140	0.161	0.245
Manager's age	Years	47	8	30	42	45	54	65

Note: Forty-one farms, four years, 164 observations in total.

in input quantities, and changes in technical efficiency to the decline in Ukrainian grain production over 1989–92. We formulate a stochastic production frontier model, and estimate its parameters from within a Bayesian framework. The Bayesian approach pioneered in the technical efficiency literature by Broeck et al., remedies a weakness of classical inference on firm-level technical efficiency. While maximum likelihood estimates of the components of output decline can be obtained for every firm, obtaining an estimate of the standard error of the estimator of the technical efficiency change can be challenging, as the estimator of firm-level inefficiency is inconsistent. In consequence, theoretical justification for the construction of the corresponding confidence intervals within a classical framework is not strong (Horrace and Schmidt).

Following Koop, Osiewalski, and Steel, we formulate a three-level hierarchical model, where the time-varying technical efficiency depends on farm-specific factors. Noninformative or diffuse prior distributions are chosen where possible. The model is estimated on a representative sample of Ukrainian former collective and state farms observed over 1989–92. Markov chain Monte Carlo methods are used to obtain samples from the distributions of the parameters of interest.

## Data

The study region is the mixed (central) soil-climatic zone of Ukraine. The data come from

a survey of state and collective farms in two administrative regions (*oblast*), Kyivska and Cherkaska. Summary statistics for the data used in the analysis are given in table 1. Kurkalova and Jensen provide more detail about the data.

We supplement the survey data with weather variables constructed from the information provided by the National Climatic Data Center (NCDC). As suggested in Desai, we model the effect of weather on grain yields via two variables, the average March–April and the average May–June–July temperatures. Since NCDC provides the information for one station in the area only, that in the city of Kyiv, the weather data in our study vary by years only and not by farms (table 2).

## Econometric Model

The stochastic production frontier model we postulate is a three-level hierarchical model similar to that of Koop, Osiewalski, and Steel. In level 1, the farm's logarithm of output in tons,  $\ln(y_{it})$  is modeled as

**Table 2. Temperature Data for the Kyiv Weather Station (C°)**

Variable	1989	1990	1991	1992
March–April average temperature	7.7	6.9	9.0	5.4
May–June–July average temperature	17.8	16.2	17.5	19.3

Source: Authors' calculations using monthly data from NCDC.

$$\ln(y_{it}) \mid \underbrace{u_{it}, \alpha_1, \alpha_2, \beta_0, \beta_1, \dots, \beta_5, \sigma_v^2}_{\text{parameters}};$$

$$\underbrace{z_{1t}, z_{2t}, x_{1it}, \dots, x_{5it}}_{\text{data}} \sim N\left(\beta_0 + \alpha_1 z_{1t} + \alpha_2 z_{2t} + \sum_{j=1}^5 \beta_j \ln(x_{jit}) - u_{it}, \sigma_v^2\right)$$

that is,  $\ln(y_{it}) = \beta_0 + \alpha_1 z_{1t} + \alpha_2 z_{2t} + \sum_{j=1}^5 \beta_j \ln(x_{jit}) + v_{it} - u_{it}.$

Here the subscript  $i$  refers to the  $i$ th farm ( $i = 1, \dots, 41$ ), the subscript  $t$  indicates the  $t$ th year ( $t = 1989, 1990, 1991, 1992$ ), and the notation  $N(a, b)$  is used for a normal distribution with mean  $a$  and variance  $b$ . The  $z_{1t}$  is the average March-April temperature in year  $t$  (in  $^{\circ}\text{C}$ ),  $z_{2t}$  is an average May-June-July temperature in year  $t$  (in  $^{\circ}\text{C}$ ),  $x_{jit}$  ( $j = 1, \dots, 5$ ) represent production inputs: land under grain production (in hectares), labor in grain production (in 1000 hours), organic fertilizer (in 100 tons), chemicals applied for grain production (in tons), and diesel fuel used in grain production (a proxy for machinery services) (in 1000 liters), respectively. The random component  $v_{it}$  is white noise representing effects on a firm's output not in the model. The nonnegative random variable  $u_{it}$  denotes the firm's technical inefficiency, that is, by how much the logarithm of the firm's output falls short of the logarithm of the maximum possible output obtainable given the weather in year  $t$ , technology, and the quantities of inputs available. The  $\alpha$ 's, the  $\beta$ 's, the  $u$ 's, and the  $\sigma_v^2$  are the quantities of interest. Conditional on the data and the parameters, the outputs  $\ln(y_{it})$  are independent (i.e., conditionally exchangeable) for all  $i$  and  $t$ .

In level 2, the technical inefficiency is modeled as an exponential random variable

$$u_{it} \mid \underbrace{\phi_1, \dots, \phi_7}_{\text{parameters}}; \underbrace{w_{1it}, \dots, w_{7it}}_{\text{data}}$$

$$\sim \text{Gamma}\left(1, \prod_{j=1}^7 \phi_j^{w_{jit}}\right).$$

Here  $w_{1it} = 1$  for all  $i$  and  $t$ , and the  $w_{jit}$ ,  $j = 2, \dots, 7$ , represent the factors affecting inefficiency. The notation  $\text{Gamma}(a, b)$  is used for a gamma distribution with mean  $a/b$  and vari-

ance  $a/b^2$ . The nonnegative  $\phi$ 's are the quantities of interest.

Following Kurkalova and Jensen, we included the following six factors in the model: the ratio of nonagricultural workers to the total number of workers on the farm, the number of agricultural workers per hectare of agricultural land, manager's age, and year indicators for 1990, 1991, and 1992. Since the focus of this study is the output change decomposition rather than explanation of technical efficiency, we refer to Kurkalova and Jensen for an in-depth discussion of the effects.

Dichotomous  $w$ 's significantly lessen computational burden as the corresponding conditional posterior distributions are of standard form (Koop, Osiewalski, and Steel). In consequence, we constructed the following dummy variables:  $w_{2it}$  is one if the ratio of nonagricultural to total workers on the farm  $i$  in time  $t$  is greater than the sample median, and zero otherwise;  $w_{3it}$  is one if the number of agricultural workers per hectare of agricultural land on the farm  $i$  in time  $t$  is greater than the sample median and zero otherwise;  $w_{4it}$  is one if the age of the farm's manager is higher than the sample first quartile and zero otherwise;  $w_{5it}$  is one if the year is 1990 and zero otherwise,  $w_{6it}$  is one if the year is 1991, and  $w_{7it}$  is one if the year is 1992 and zero otherwise.

In level 3, the priors for the parameters  $\beta_0, \beta_1, \dots, \beta_5, \alpha_1, \alpha_2, \sigma_v^2$ , and the hyperparameters  $\phi_1, \dots, \phi_7$  are specified.

The Bayesian approach to estimation combines the information about model parameters that are available from all sources. Information contained in the data is summarized in the likelihood function. Prior knowledge (or lack thereof) about the model parameters is summarized into the prior distributions chosen for those parameters. Bayes' theorem provides a mechanism to combine both sources of information into the posterior density of the quantities of interest. In stochastic frontier models, we are also interested in the firm efficiencies, which are functions of  $u_{it}$ 's.

**Prior Distributions**

We used noninformative prior distributions when possible:

$$\beta_k \sim \text{Unif}(-\infty, \infty), \quad k = 0, \dots, 5;$$

$$\alpha_k \sim \text{Unif}(-\infty, \infty), \quad k = 1, 2;$$

$$\sigma_v^{-2} \mid p_1, p_2 \sim \text{Gamma}(p_1, p_2);$$

$$\phi_j \sim \text{Gamma}(a_j, g_j),$$

where  $a_j = g_j = 1$  for  $j > 1$ , and  $a_1 = 1, g_1 = -\ln(r^*)$ , with an  $r^* \in (0, 1)$ .

Note that the choice of improper prior distributions for some of the parameters still results in an integrable posterior distribution. A Gamma prior distribution is a widely used choice for the inverse of the variance parameters in normal models (Gelman et al.). Fernandez, Osiewalski, and Steel have shown that the parameter  $p_2$  must be positive, as otherwise the posterior distribution in the inefficiency model does not exist. We set  $p_1 = 1, p_2 = 0.01$ , implying that a priori, the expected value of  $\sigma_v^{-2}$  was equal to 100. The relatively noninformative prior distributions of  $\varphi$ 's are chosen following Koop, Osiewalski, and Steel. If the explanatory variables  $w_j, j = 2, \dots, 7$ , have no effect on the distribution of  $u_{it}$ , then the prior median efficiency would be  $r^*$ . The parameter  $r^*$  was chosen to be 0.8, because this is the value reported in many studies of technical efficiency of (post-) Soviet agriculture (e.g., Sedik, Truebold, and Arnade; Johnson et al.; Sotnikov).

### Posterior Distributions and the Gibbs Sampler

The joint posterior distribution that results from combining the likelihood function and the prior distributions is an unwieldy multivariate function. Thus, derivation of the posterior marginal distributions of the parameters is not analytically tractable. We use a numerical approach, the Gibbs sampler, which permits obtaining a sample from the joint posterior distribution of all parameters by taking random draws from only full conditional distributions (see, e.g., Gelman et al., for a detailed description of this technique). The  $u_{it}$ 's are included into the set of the random quantities for which we obtain the joint posterior distribution using the Gibbs sampler.

The conditional posterior distributions of the quantities of interest,  $\bar{u}, \hat{\beta}, \bar{\alpha}, \sigma_v^2, \hat{\varphi}$ , are used to implement a Gibbs sampler.<sup>1</sup> That is, the distributions of  $\theta_i | \theta_{(-i)}$ ; data are used, where  $\theta \equiv (\bar{u}, \hat{\beta}, \bar{\alpha}, \sigma_v^2, \hat{\varphi})$ ,  $\theta_i$  is a subvector of  $\theta$ ,  $\theta_{(-i)}$  is  $\theta$  without the element  $\theta_i$ , and data include  $\bar{y}, \bar{z}, \bar{x}$ , and  $\bar{w}$ . All conditional posterior distributions in the model have standard densities (truncated normal, multivariate normal,

or Gamma) (Koop, Osiewalski, and Steel), and are given in the appendix.

Briefly, the Gibbs sampler proceeds as follows. A value of each parameter in the model is drawn from its corresponding conditional distribution. The sequence of draws obtained in this manner, forms a Markov chain, whose stationary distribution is equal to the marginal posterior distribution of the parameter. Gelman et al. provide the proof for the above result, and list the conditions that must be met for good performance of the method. In practice, we start with "guesses" for the values of the parameters in the model, and proceed sequentially, drawing a value from each of the full conditional distributions described earlier. After a suitably large number of Gibbs steps, the draws from the conditionals can be thought of as draws from the corresponding marginal posterior distributions. While convergence of the chains to their stationary distributions is very hard to assess exactly, the behavior of the chains can be monitored, and "convergence" can then be assumed. Further details on the Gibbs sampler, including convergence criteria and application to the estimation of technical efficiency models are available in Koop, Osiewalski, and Steel, and in Osiewalski and Steel.

Implementation of the Gibbs sampler results in a (correlated) sample of draws of the model parameters. In each pass, draws from the decomposition of output change in its components can be constructed for every firm. Specifically, as the rate of change of output over time is defined as  $\dot{y}_{it} \equiv \frac{1}{y_{it}} \frac{dy_{it}}{dt} = \frac{d \ln y_{it}}{dt}$ , a discrete estimate of the rate of change of output over the years 1989–92 can be decomposed as

$$\begin{aligned} & \widehat{\ln(y_{i,92})} - \widehat{\ln(y_{i,89})} \\ &= \underbrace{\sum_{j=1}^2 \hat{\alpha}_j (z_{j,92} - z_{j,89})}_{\text{due to weather variability}} \\ &+ \underbrace{\sum_{j=1}^5 \hat{\beta}_j (\ln(x_{ji,92}) - \ln(x_{ji,89}))}_{\text{due to a change in input quantities}} \\ &+ \underbrace{(\hat{u}_{i,89} - \hat{u}_{i,92})}_{\text{due to a change in technical efficiency}} \end{aligned}$$

where a hat over a parameter denotes an estimate. Once the draws are obtained, the posterior distributions of the quantities of interest can be approximated and easily summarized

<sup>1</sup> The notation  $\bar{x}$  is used for a vector/matrix  $x$  of the appropriate dimension.

via histograms and descriptive statistics such as means, variances, and percentiles. The Bayesian approach allows estimation of probabilities of the form  $\Pr[\theta \in \Delta]$ , where  $\theta$  is a random quantity of interest, and  $\Delta$  is a one-dimensional set. For example, we can make statements such as “The probability that a decline in input quantities contributed between 40% and 70% to the overall decline in the production of firm X is Y%.”

We generated five independent chains, each of length 5000, but combined only the last 4000 draws from each chain to approximate the posterior distributions of interest. Initial values for  $\beta_0, \alpha_1, \alpha_2$  for the five independent Markov chains were drawn independently from the  $Unif(-10,10)$  distribution. Initial values for the rest of the  $\beta$ 's were drawn from  $Unif(0,1)$ , since these parameters represent the output elasticities. The initial values for  $\sigma_v^{-2}$  and  $\bar{\varphi}$  were drawn independently from the corresponding prior distributions. Overall, results were insensitive to starting values.

The behavior of the chains was monitored with the statistic  $\sqrt{\hat{R}}$  (Gelman et al.). Intuitively, the statistic monitors convergence by comparing the within- and between-chain vari-

ances. If the chains have converged to their stationary distributions, the value of the statistic is approximately equal to 1. Values larger than 1 indicate that the “noise” in the draws can be reduced by an amount equivalent to the excess of 1 if the chains are allowed to proceed to additional steps. In our application, the values of the  $\sqrt{\hat{R}}$  statistic were under 1.02 for all parameters after 5000 iterations, indicating that additional Gibbs steps would not have resulted in increased precision of our estimates.

## Results

Results are summarized in table 3. The estimated positive effect of spring temperatures and the negative effect of summer temperatures on grain production are consistent with agronomic science. While higher spring temperatures help melt snow and promote winter plant growth, high temperatures after planting of the spring crop deprive the germinating seeds of moisture and, therefore, reduce yields. Desai found similar effects on a twenty-two-year time series of grain yield data for the pretransition Kyivska oblast (one of the

**Table 3. Bayesian Estimates for Parameters of the Frontier Model**

Variable	Parameter	Posterior Distributions <sup>a</sup>		
		Median	St. Dev.	Selected Probabilities
<b>Stochastic frontier</b>				
Constant	$\beta_0$	5.32	0.67	$\Pr[\beta_0 > 0] = 100.0\%$
April-May Av. Temp.	$\alpha_1$	0.007	0.023	$\Pr[\alpha_1 > 0] = 62.6\%$
May-June-July Av. Temp.	$\alpha_2$	-0.043	0.021	$\Pr[\alpha_2 < 0] = 98.6\%$
Ln (Land)	$\beta_1$	0.16	0.13	$\Pr[\beta_1 > 0] = 88.2\%$
Ln (Labor)	$\beta_2$	0.058	0.028	$\Pr[\beta_2 > 0] = 98.3\%$
Ln (Fertilizer)	$\beta_3$	0.135	0.032	$\Pr[\beta_3 > 0] = 100.0\%$
Ln (Chemicals)	$\beta_4$	0.283	0.048	$\Pr[\beta_4 > 0] = 100.0\%$
Ln (Fuel)	$\beta_5$	0.309	0.093	$\Pr[\beta_5 > 0] = 99.9\%$
Standard deviation	$\sigma_v$	0.148	0.013	
<b>Inefficiency model</b>				
Constant	$\varphi_1$	16.2	4.8	$\Pr[\varphi_1 > 1] = 100.0\%$
Dummy for proportionately higher nonagricultural employment	$\varphi_2$	1.44	0.42	$\Pr[\varphi_2 > 1] = 92.3\%$
Dummy for higher agricultural workers per hectare	$\varphi_3$	2.07	0.60	$\Pr[\varphi_3 > 1] = 99.8\%$
Dummy for higher manager's age	$\varphi_4$	1.72	0.63	$\Pr[\varphi_4 > 1] = 95.6\%$
Dummy for 1990	$\varphi_5$	0.56	0.64	$\Pr[\varphi_5 < 1] = 81.2\%$
Dummy for 1991	$\varphi_6$	0.136	0.058	$\Pr[\varphi_6 < 1] = 100.0\%$
Dummy for 1992	$\varphi_7$	0.54	0.61	$\Pr[\varphi_7 < 1] = 81.9\%$
<b>Average (over farms) change in Ln (output), 1989–92</b>				
Due to weather		-0.084	0.049	$\Pr[\text{change} < 0] = 95.4\%$
Due to a change in input quantities		-0.202	0.018	$\Pr[\text{change} < 0] = 100.0\%$
Due to a change in technical efficiency		-0.041	0.039	$\Pr[\text{change} < 0] = 88.8\%$

<sup>a</sup>Computed from 20,000 runs of the Gibbs sampler after discarding the first 5000 draws.

regions surveyed in our data). The magnitudes of the output elasticities<sup>2</sup> are also in general agreement with previous studies on crop production in the former Soviet Union (Johnson et al., Kurkalova and Jensen, Sedik, Truebold, and Arnade).

By construction, the  $\varphi$ 's different from one indicate a significant effect on technical inefficiency. A value of  $\varphi_j$  ( $j=2, \dots, 7$ ) greater than one indicates a negative effect of the corresponding variable on technical inefficiency, and thus a positive effect of the variable on technical efficiency. As seen from table 3, most of the inefficiency effects are different from one, and in agreement with the analysis of Kurkalova and Jensen.

The positive effect of the proportion of nonagricultural workers in total farm employment on technical efficiency is consistent with better farm-provided infrastructure that may have played a positive role in keeping up technical efficiency during the transition-related dismantling of production networks. The number of agricultural workers per hectare can be thought of as an indicator of past farm performance—the better the farm performed the more people remained on it over time. The estimated effect thus indicates that the farms that were doing better in pretransition times are also doing better in terms of technical efficiency during early transition. Sedik, Truebold, and Arnade also note the importance of initial conditions on predicting farm efficiency performance during transition. The estimated positive effect of manager's age, a proxy for experience, indicates that human capital is an important factor in achieving technical efficiency; this is consistent with studies of efficiency of agricultural production worldwide (Battese, Bravo-Ureta and Pinheiro). The median of the posterior distribution of the average (across farms and years) technical efficiency was found to be 0.909 with a standard deviation of 0.019.

The estimates of the average across farm components of output decline are largely negative (table 3). We estimated the posterior distributions of the proportions of the components of output decline in the total output decline for every farm in the sample, and those of averages across farms. That is, we estimated the posterior distributions of both  $p_{ji}$  and  $p_{jav}$ , where

$$p_{ji} = s_{ji} / (s_{1i} + s_{2i} + s_{3i}), \quad j = 1, 2, 3, \\ i = 1, \dots, 41$$

$$s_{1i} = \sum_{j=1}^2 \hat{\alpha}_j (z_{j,92} - z_{j,89})$$

$$s_{2i} = \sum_{j=1}^5 \hat{\beta}_j (\ln(x_{ji,92}) - \ln(x_{ji,89}))$$

$$s_{3i} = \hat{u}_{i,89} - \hat{u}_{i,92}, \text{ and } p_{jav} \equiv \frac{1}{41} \sum_{i=1}^{41} p_{ji}.$$

The biggest share of the total decline corresponds to the decline in the quantities of inputs: the median of  $p_{2av}$  is estimated to be 0.56 with  $\Pr[0.4 \leq p_{2av} \leq 0.8] = 0.91$ , and for fifteen farms in the sample,  $\Pr[p_{2i} \geq 0.5] \geq 0.90$ . The next biggest share of the total decline is due to weather: the median of  $p_{1av}$  is 0.35 with  $\Pr[0.1 \leq p_{1av} \leq 0.6] = 0.85$ . The smallest share of the output decline is due to a decline in technical efficiency: the median of  $p_{3av}$  is estimated to be 0.09 with  $\Pr[0 \leq p_{3av} \leq 0.3] = 0.70$ , and for some thirty farms in the sample  $\Pr[p_{3i} \leq 0.3] \geq 0.70$ . Note that making such farm-level inference from a classical prospective would be much harder to do because of inconsistency of the ML estimator  $\hat{u}_{i,t}$  and non-linearity of the quantities of interest.

## Conclusion

This study aims to quantify some of the reasons for the grain output decline in the early years of transition in Ukraine. We find that the decline in the use of production inputs accounts for over one half of the total output decline, while weather effects account for about 35% of the decline. The rest is attributable to a decline in the technical efficiency of collective farms during the transition years. The choice of the Bayesian paradigm for estimation was made to improve the reliability in the estimation of standard errors of functions of model parameters. Because we used noninformative priors where possible, posterior medians of parameters are roughly comparable to those that might have been obtained within a frequentist framework. In this paper, we did not model individual farm weather due to lack of data. However, the analysis showed that explicit modeling of weather effects is important and improves technical efficiency analysis. More detailed weather data may improve the precision of estimation.

<sup>2</sup> Often, other more general forms for the frontier production function can be more appropriate than the Cobb-Douglas form. However, earlier frequentist analysis of these data suggests that the Translog form does not fit these data better.

An intriguing extension of this work is to model explicitly the decline in factor use. The quantities of inputs used in production went down because of the break down of state distribution systems and growing prices, and may have been determined significantly by individual farm responses. Explicit modeling of input quantities used would require farm-level information on input prices, uncertainties in delivery systems, and other information on factors affecting acquisition of production inputs during the early transition.

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## Appendix

Throughout the appendix,  $p(\cdot)$  denotes the probability density function of an appropriate random variable,  $f_G(x | a, b)$  denotes the probability density function of a Gamma distribution with a mean  $a/b$  and a variance  $a/b^2$ , that is,  $f_G(x | a, b) \equiv \frac{b^a}{\Gamma(a)} x^{a-1} e^{-bx}$ ,  $\Gamma(\cdot)$  is a Gamma function, and  $\Phi(\cdot)$  is a cumulative density function of the standard Normal distribution.

The full conditional posterior of  $u_{it}$  is a truncated Normal distribution:

$$\begin{aligned}
 & p(u_{it} | \bar{\beta}, \bar{\alpha}, \sigma_v^2, \bar{\phi}; y_{it}, z_{1t}, z_{2t}, x_{1it}, \dots, \\
 & \quad x_{5it}, w_{2it}, \dots, w_{7it}) \\
 & = \frac{1}{\sqrt{2\pi} \sqrt{\sigma_v^2} \Phi\left(\frac{m_{it}}{\sqrt{\sigma_v^2}}\right)} \\
 & \quad \times \exp\left\{-\frac{1}{2\sigma_v^2}(u_{it} - m_{it})^2\right\}, \quad u_{it} \geq 0
 \end{aligned}$$

where

$$m_{it} \equiv -\ln(y_{it}) - \sigma_v^2 \prod_{j=1}^7 \varphi_j^{w_{jit}} + \beta_0 + \alpha_1 z_{1t} + \alpha_2 z_{2t} + \sum_{j=1}^5 \beta_j \ln(x_{jit}).$$

The full conditional posterior of  $\bar{\mathbf{B}} \equiv (\beta_0, \alpha_1, \alpha_2, \beta_1, \dots, \beta_5)$  is an 8-variate Normal distribution:  $p(\bar{\mathbf{B}} | \bar{u}, \sigma_v^{-2}; \bar{z}, \bar{x}, \bar{y}) \propto \exp\{-\frac{1}{2}\sigma_v^{-2} \times (\bar{\mathbf{B}} - \bar{\mu})'(\bar{\mathbf{X}}'\bar{\mathbf{X}})(\bar{\mathbf{B}} - \bar{\mu})\}$ ,  $\bar{\mathbf{B}} \in \mathbf{K}(\bar{\mathbf{B}})$  where  $\bar{\mu} = (\bar{\mathbf{X}}'\bar{\mathbf{X}})^{-1}\bar{\mathbf{X}}'(\ln(\mathbf{y}) + \bar{u})$ ,  $\mathbf{K}(\bar{\mathbf{B}}) = \times_{j=1}^8 (-\infty, \infty)$ , and  $\bar{\mathbf{X}}$  is a 164 by 8 matrix consisting of the rows  $(1, z_{1t}, z_{2t}, \ln(x_{1it}), \dots, \ln(x_{5it}))$ ,  $t = 89, \dots, 92$ ,  $i = 1, \dots, 41$ .

The full conditional posterior of  $\sigma_v^{-2}$  is a Gamma distribution

$$p(\sigma_v^{-2} | \bar{u}, \bar{\alpha}, \bar{\beta}; \bar{z}, \bar{x}, \bar{y}; p_1, p_2) = f_G\left(\sigma_v^{-2} \mid \frac{p_1 + 164}{2}, \frac{1}{2}\right) p_2 + \sum_{t=89}^{92} \sum_{i=1}^{41} \left(\ln(y_i) + u_{it} - \beta_0 - \alpha_1 z_{1t}\right.$$

$$\left. - \alpha_2 z_{2t} - \sum_{j=1}^5 \beta_j \ln(x_{jit})\right)^2 \Bigg), \quad \sigma_v^{-2} \geq 0.$$

The full conditional distribution of  $\varphi_1$  is a Gamma distribution

$$p(\varphi_1 | \bar{u}, \bar{\varphi}_{(-1)}; \bar{w}; a_1, g_1) = f_G\left(\varphi_1 | a_1 + 164, g_1 + \sum_{t=89}^{92} \sum_{i=1}^{41} u_{it} D_{1it}\right), \quad \varphi_1 \geq 0.$$

Here  $D_{rit} \equiv \prod_{j \neq r} \varphi_j^{w_{jit}}$ ,  $r = 1, \dots, 7$ ,  $i = 1, \dots, 41$ ,  $t = 89, \dots, 92$ , and  $\bar{\varphi}_{(-j)}$  denotes  $\bar{\varphi}$  without its  $j$ th element.

Finally, the full conditional distributions of  $\varphi_j$ ,  $j = 2, \dots, 7$ , are also Gamma distributions:

$$p(\varphi_j | \bar{u}, \bar{\varphi}_{(-j)}; \bar{w}; a_j, g_j) = f_G\left(\varphi_j | a_j + \sum_{t=89}^{92} \sum_{i=1}^{41} w_{jit}, g_j + \sum_{t=89}^{92} \sum_{i=1}^{41} w_{jit} u_{it} D_{jit}\right), \quad \varphi_j \geq 0.$$