



Volume 11, Issue 4, 2023

ORIGINAL RESEARCH PAPER

Pages: 53-73

Estimation of Red Meat Production Efficiency with an Emphasis on Separating Unobserved Heterogeneity from Efficiency: An Inter-Provincial TRE Approach

Hojjat Zabih Haghighi Rabbani¹, Leila Vaezi^{2*}, Saeed Safari Dolatabad³

1 PhD Student, Department of Agricultural Economics, Agricultural Policy and Development, Roudehen Branch, Islamic Azad University, Roudehen, Iran.

2 Department of Agricultural Economics, Agricultural Policy and Development, Roudehen Branch, Islamic Azad University, Roudehen, Iran. (Corresponding Author). Email: 1377364631@iaui.ir

3 Department of Plant Genetics and Breeding, Roudehen Branch, Islamic Azad University, Roudehen, Iran.

Received: 29 May 2023

Revised: 30 July 2023

Accepted: 28 October 2023

ABSTRACT

In conventional stochastic frontier (SF) models, the inefficiency term is assumed to be constant over time; however, in reality, inefficiency is time-dependent due to policy changes. Another issue with standard SF models is that when panel data and cross-sectional heterogeneity are utilized, fixed and random effects are confounded with the inefficiency term and are not adequately accounted for in the model, resulting in the inefficiency term being estimated as bias. Therefore, the objective of this paper is to address these two issues in estimating the stochastic production function for red meat across Iranian provinces. Specifically, the cross-sectional units comprise 32 Iranian provinces, and the corresponding time series cover annual data from 2004 to 2021. The True Random Effects (TRE) model is estimated and compared with previous models that suffered from these two issues, and its superiority is confirmed through the Wald test. The three most efficient provinces in terms of red meat production are Ilam, Kurdistan, and Kerman, respectively, while the three least efficient provinces are Khorasan Razavi, Golestan, and Tehran. The provinces that have experienced a continuous decrease in red meat distribution inefficiency include Khuzestan, Zanjan, Sistan and Baluchestan, East Azerbaijan, Alborz, Isfahan, Bushehr, Tehran, and North Khorasan. Conversely, several provinces, including Semnan and Chaharmahal and Bakhtiari, have exhibited an increasing trend in inefficiency.

KEYWORDS: Stochastic Frontier, Cross-Sectional Heterogeneity, Red Meat Production, Technical Efficiency, Inefficiency Effects

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How to Cite This Article: Zabih Haghighi Rabbani, H.Z., Vaezi, L., Safari Dolatabad, S. (2023). "Estimation of Red Meat Production Efficiency with an Emphasis on Separating Unobserved Heterogeneity from Efficiency: An Inter-Provincial TRE Approach". *The Open Access Journal of Resistive Economics*, 11(4): 53-73.

1. Introduction

One of the prominent research streams in the economics literature is the analysis of productivity and efficiency using the frontier function approach. These models provide performance measures in terms of potential input contraction or potential output expansion relative to a "best-practice" reference frontier constructed from observable inputs and outputs. The frontier function model, introduced by Farrell (1957), provided a framework for defining and measuring different types of efficiency: technical efficiency (TE), which measures a firm's ability to obtain maximum output from a given set of inputs; allocative efficiency (AE), which measures a firm's ability to use inputs in optimal proportions given their prices; and overall economic efficiency (EE), which is the product of TE and AE.

In agricultural economics, frontier function approaches have served as the foundation for a highly fruitful area of research. Frontier models are generally classified into two categories: parametric and non-parametric. Parametric methods require the specification of a functional form for production (such as Leontief, Cobb-Douglas, translog, etc.), whereas non-parametric models do not, which constitutes the primary advantage of the latter. Parametric models can be further divided into deterministic and stochastic frontier analysis (SFA). The former assumes that any deviation from the frontier is due to inefficiency, while the stochastic approach incorporates a statistical error term. Consequently, a key limitation of deterministic frontiers is that measurement errors, along with other sources of random variation, are treated as inefficiency, meaning that outliers can have a distorting effect on TE scores.

The stochastic frontier model, proposed by Meeusen and van den Broeck (1977), addressed the issue of outliers by employing a composed error term consisting of a symmetric two-sided random component and a one-sided inefficiency component. The two-sided error term accounts for random shocks beyond the firm's control, while the one-sided component captures technical inefficiency. However, a limitation of conventional stochastic frontier models is that the inefficiency term was traditionally assumed to be time-invariant, whereas in reality, inefficiency varies over time. Another issue with conventional models is that when utilizing panel data, cross-sectional heterogeneity is often modeled through fixed or random effects. If these effects are not properly accounted for in the model, cross-sectional heterogeneity can be confounded with the inefficiency term. Consequently, what should be estimated as fixed or random effects becomes entangled with the inefficiency term, leading to biased estimates of inefficiency. These two issues have been highlighted in previous studies, including research conducted in Iran. To address them, a model has been employed that accommodates time-varying inefficiency while properly disentangling the effects of unobserved cross-sectional heterogeneity. The objective of this paper is to address these two issues in estimating the stochastic frontier production function for red meat across Iranian provinces. Specifically, our objectives are as follows:

- Calculating the efficiency scores of various provinces in red meat production by disentangling unobserved heterogeneity from provincial efficiency.
- Comparing the inefficiency scores derived from this model over time for each province.
- Examining the aforementioned inefficiency model and comparing it with the conventional model.

- Estimating efficiency scores and analyzing the temporal trends of provincial inefficiency within the framework of the preferred model.
- Ranking the efficient and inefficient provinces in red meat production across the country.

The cross-sectional units comprise the Iranian provinces, totaling 32 provinces based on the administrative divisions established in recent years. The corresponding time series span the 2000s and 2010s. Specifically, the data are annual, covering the period from 2004 to 2021. Therefore, the statistical population used in this study comprises data on the production and inputs of red meat across Iranian provinces over the aforementioned years.

The remainder of this paper is organized as follows. First, a review of the literature on stochastic frontier models is presented, encompassing both theoretical foundations and empirical background. Next, an analysis of the descriptive statistics for the data used in model estimation is provided. Subsequently, the theoretical framework of the proposed model is outlined, and the empirical model is estimated. Following this, the research hypotheses are tested, the estimated provincial efficiency scores are presented, and the temporal trends of these scores are analyzed. Additionally, the efficiency ranking of the provinces is illustrated. Finally, the paper concludes with a summary and concluding remarks.

2. Theoretical Foundations and Literature Review

Frontier models have been widely used in applied economics due to their alignment with the neoclassical optimization concept embedded in profit, production, revenue, or cost function definitions. The popularity of frontier analysis and related models has been demonstrated by the proliferation of methodological and empirical frontier studies over the past four decades. At the global level, methodological reviews covering a wide range of models can be found in Forsund, Lovell, and Schmidt (1980), Seiford and Thrall (1990), Bauer (1990), Kumbhakar and Lovell (2000), Greene (2008), Lovell and Schmidt (2008), Lachaud, Bravo-Ureta, and Ludena (2017), among others. The popularity of applied frontier models in agricultural economics has been documented in several reviews, including Battese (1992), Bravo-Ureta and Pinheiro (1993), Gorton and Davidova (2004), Bravo-Ureta et al. (2007), and Moreira and Bravo-Ureta (2009).

Regarding studies conducted over the last two decades, Dashti et al. (2013) investigated the relationship between efficiency and sustainability in potato farms in Kaboudar Ahang County. By administering questionnaires to 219 potato farmers during the 2002–2003 crop year, they calculated the average technical efficiency of the farms to be 99%. Additionally, based on the obtained results, it was observed that the technical efficiency of the farms ranged from 19% to 81%. Dorandish et al. (2013) estimated the multiproduct technical efficiency of farms in North Khorasan Province using two approaches: the stochastic frontier production function and the stochastic distance frontier function. The estimation results of the stochastic frontier models indicated that the average technical efficiency calculated by this model was 89%. Heriqbaldi et al. (2014) estimated the technical efficiency of rice farms in Indonesia using the stochastic frontier production function approach. The results revealed significant inefficiency among the 21 provinces studied. Furthermore, younger farmers were found to be more efficient. They concluded that expanding agricultural lands, particularly outside the islands of Java and

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Sumatra, would improve farmers' incomes, encourage youth to engage in the agricultural sector, enhance technical efficiency, and consequently boost both productivity and rice production.

Usman et al. (2016) estimated the technical, allocative, and economic efficiency of wheat farms in Layyah, Pakistan. The results for technical, allocative, and economic efficiency were 99%, 92%, and 19%, respectively. Kavand et al. (2014) utilized data envelopment analysis to estimate the technical, economic, and allocative efficiency of saffron producers in Qain County. The results indicated that under constant returns to scale, the mean technical, allocative, and economic efficiencies were 0.91, 0.81, and 0.99, respectively, whereas under variable returns to scale, they were 0.98, 0.81, and 0.90, respectively.

In a study titled "Analysis of Technical Efficiency and Technology Gap of Broiler Poultry Units in Sanandaj County," Dashti et al. (2015) argued that the limitation of production resources in various societies has led to an increase in diverse agricultural outputs, with a special emphasis on enhancing production productivity. In this context, improving the efficiency of production units and their technology gap ratio is considered a practical solution for enhancing factor productivity. The objective of this study was to analyze the efficiency and technology gap of broiler poultry farms in Sanandaj County. The required statistics and information were obtained from the Kurdistan Province Agricultural Jihad Organization for the period 2018–2019. An econometric approach, employing the estimation of the stochastic frontier production function and the metafrontier function, was utilized for this research. The estimation of the group metafrontier production function revealed that the technical efficiency for different groups ranged from 89% to 95%, the mean technical efficiency based on the metafrontier production function ranged from 44% to 76%, and the technology gap ratios for the groups were 0.84 and 0.46, respectively.

Mardani and Salarpour (2015) employed data envelopment analysis to examine the technical efficiency of 19 Iranian provinces in potato production. This method was based on seven inputs (labor, land, diesel fuel, machinery, irrigation water, fertilizer costs, and pesticide costs) and the potato output. According to this study, the mean technical efficiency was calculated to be 80%. Tavva et al. (2017) estimated the technical efficiency of five major wheat-producing provinces in Afghanistan using the stochastic frontier function approach. The mean technical efficiency of these farms was calculated at 17%, implying that wheat production could be increased by enhancing farm efficiency at the same level of input consumption.

Khodavardizadeh et al. (2018), in a study on determining the technical efficiency of wheat production with an emphasis on sustainable agriculture in Urmia County, emphasized the optimal use of resources. The goal of sustainable agriculture is to achieve maximum technical productivity due to the scarcity of agricultural resources. In this research, the technical efficiency of wheat production in Urmia County was estimated using two methods: data envelopment analysis and the stochastic frontier function approach. The required data and information were collected through questionnaires distributed among 201 wheat farmers in the county during the 2003–2009 crop years. The results indicated that the mean technical efficiency using the DEA and SFA methods was 71% and 12%, respectively. Thus, the crop yield can be increased without utilizing more inputs or increasing costs. In line with sustainable agriculture, enhancing the technical efficiency of producers is considered one of the efficient

methods for increasing production. Although the aforementioned studies are by no means exhaustive, for the sake of brevity, we now proceed to the descriptive analysis of the data used in the study.

3. Research Methodology

The present study is applied in terms of its objective and descriptive-analytical in nature, employing an econometric approach and panel data. The statistical population of this study comprises the 32 provinces of the country over an 18-year period (2004–2021), and the required data have been extracted from the statistical yearbooks of the Ministry of Jihad Agriculture. In this research, the stochastic frontier production function with a Cobb-Douglas functional form is estimated, wherein the logarithm of red meat production is considered the dependent variable, and the logarithms of forage consumption, sheep and goat population, and cattle and calf population are treated as independent variables (production inputs).

From an econometric methodology perspective, to address the limitations of conventional stochastic frontier models and disentangle "unobserved cross-sectional heterogeneity" from "time-varying technical inefficiency," the True Random Effects (TRE) model proposed by Greene (2005) is utilized. In this model, the two-sided error term is decomposed into two components of time-invariant heterogeneity and random shocks to prevent the biasing of inefficiency scores. The model parameters are estimated using the Maximum Likelihood Estimation (MLE) method, and the Wald test is employed to demonstrate the superiority of the TRE model over conventional frontier models. Ultimately, the technical efficiency scores of the provinces are calculated and analyzed by accounting for the effects of unobserved heterogeneity.

4. Findings

Analysis of Descriptive Statistics

Prior to estimating the model in the subsequent section of the paper, it is necessary to scrutinize the data employed in the model more rigorously and to present a descriptive statistical analysis. As articulated in the primary objectives of this paper, conventional inefficiency estimation models in panel studies largely overlook unobserved cross-sectional heterogeneity. Consequently, our objective is to estimate cross-sectional inefficiency while accounting for this unobserved heterogeneity. As with any empirical study, we must estimate either a production or a cost function. By opting to estimate a production function, we recognize that the dependent variable represents the output quantity. Thus, our objective is to specify a production function wherein the dependent variable is the volume of red meat production across the provinces over various years. Conversely, the production function necessitates production factors or inputs. Therefore, a more detailed examination of the data pertaining to the dependent variable in this study is warranted. To this end, the first section presents and graphically analyzes data concerning red meat production across the country's provinces. Drawing on data from 2004 to 2021, the trend of red meat production in each province is delineated and analyzed. Descriptive statistics for red meat production data across the 32 studied provinces have been compiled.

These statistics encompass the mean, maximum, and minimum red meat production figures, alongside the standard deviation, skewness, and kurtosis. The source of the reported statistics is the statistical yearbook published by the Ministry of Jihad Agriculture.

In this section, we interpret the trends in red meat production for each province. The first province examined is East Azerbaijan, where production exhibited an upward trajectory until 2006. Following a one-year decline in the 2010s, the increasing trend resumed, albeit at a much more moderate pace. The next province analyzed is West Azerbaijan, which displays a production trend highly analogous to that of East Azerbaijan; it demonstrated an upward trajectory until the mid-2000s, followed by a relative dip in the late 2000s before production increased again, maintaining a relatively stable upward trend. A similar pattern is observed in the third province, Ardabil, mirroring the trends in West and East Azerbaijan. Production rose at a relatively steep incline until the mid-2000s, followed by a resurgence after a relative dip leading into the early 2010s. The fourth province examined is Isfahan, which showed a steady increase in red meat production throughout the 2000s; after a one-year drop in 2006, production surged at a comparatively steeper rate toward the end of the period. In Alborz province, red meat production has increased at a relatively steep rate since the late 2000s, coinciding with the publication of the province's official statistics, although production growth experienced fluctuations around 2018.

Ilam is one of the provinces characterized by severe production fluctuations; specifically, red meat production in this province maintained a relatively stable trend until the early 2010s, but experienced a sharp spike in 2014 and 2015. However, the data indicate that following a stable period in the late 2010s, a downward trend in production emerged in this province, with this decline intensifying towards the end of the 2010s. Bushehr is among the provinces where the red meat production trend resembles a descending step function; specifically, from the mid-2000s to the early 2010s, red meat production in this province was accompanied by a severe decline. Subsequently, the trend remained completely stable until 2020. Tehran province exhibits a parabolic, U-shaped trend in red meat production during the 2000s and 2010s; meaning that red meat production in this province plunged at a steep downward slope starting in 2006, reaching its trough and remaining at this bottom level until 2013, before finally initiating an increase in production from 2020 onward. Chaharmahal and Bakhtiari province also displays a parabolic curve in its red meat production trend. However, this parabolic curve deviates from a uniform pattern, and numerous fluctuations in the province's production are observed on a year-by-year basis. Red meat production in this province plummeted to its lowest level in the mid-2000s due to a severe decline, and while it experienced fluctuations until 2011, it showed a slight increase in 2004, ultimately returning to its steady fluctuating trend in the late 2010s. South Khorasan province has exhibited a sinusoidal downward trend in red meat production; specifically, from the mid-2010s to the late 2010s, red meat production in this province has been on a downward trajectory, yet the trend comprises two cycles with two peaks and two troughs. Therefore, production fluctuations in this province possess both positive and negative amplitudes. During the 2010s, Razavi Khorasan province experienced a slight increase in red meat production; although this gentle trend is evident throughout the period, a severe decline in red meat production was observed in this province in the mid-2000s and early 2010s. North Khorasan province maintained a highly stable production trend following a

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drastic drop in the second half of the 2000s and throughout the 2010s. This stable trend indicates very minor changes, meaning that production experienced minimal fluctuations during this period. Khuzestan province demonstrated an increasing trend in red meat production until the mid-2000s; however, in 2006, it recorded the lowest production level due to a severe drop, before ultimately beginning to increase in a sinusoidal pattern starting in 2008. Zanjan province rapidly increased its red meat production until the early 2000s, but faced a relative decline in the mid-2000s, after which it continued to increase its production sinusoidally until the late 2010s. During the 2000s and 2010s, Sistan and Baluchestan province exhibited an overall increasing trend in red meat production, despite experiencing a production drop in the early and mid-2000s. With the exception of a sharp spike in 2005, it has experienced a stable production process with severe fluctuations, meaning that at the end of the 2000s and 2010s, red meat production is nearly identical, yet there are substantial variations in red meat production throughout this period. Fars province has also experienced a proportional trend in red meat production; however, this trend peaked in the mid-2010s before indicating a decline in production. Moreover, this parabolic trend has been accompanied by fluctuations throughout its entire course. Qazvin province has experienced a very gentle, non-fluctuating upward trend in red meat production during the 2000s and 2010s. Of course, this trend had a steeper slope in the mid-2000s compared to other years. Nevertheless, the main characteristic of red meat production in Qazvin province is its minimal fluctuations, indicating that uncertainties in red meat production have been very low over these two decades. Until the mid-2010s, Qom province exhibited a red meat production process resembling a descending step function, meaning it experienced alternating periods of production decline and stability. However, since the mid-2010s, red meat production in this province has increased at a relatively rapid pace.

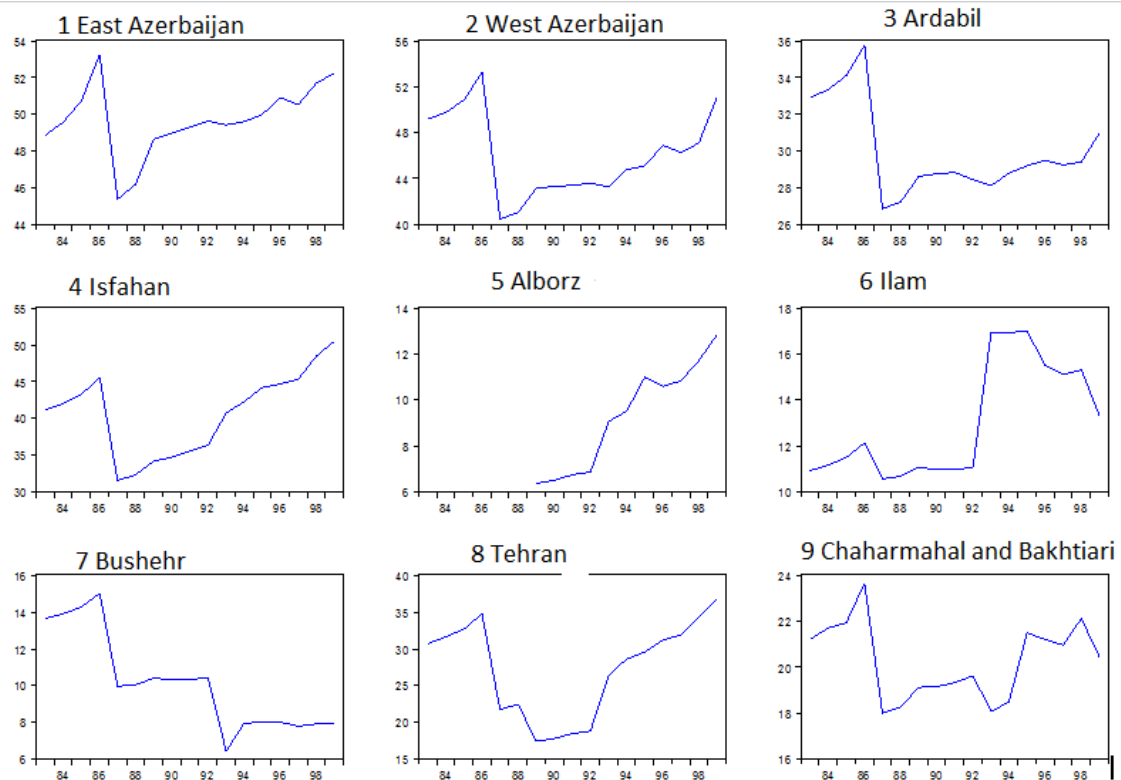


Figure1. Red meat production chart for each province of the country (first category)

Khuzestan province demonstrated an increasing trend in red meat production until the mid-2000s; however, in 2006, it recorded the lowest production level due to a severe drop, before ultimately beginning to increase in a sinusoidal pattern starting in 2008. Zanzan province rapidly increased its red meat production until the early 2000s, but faced a relative decline in the mid-2000s, after which it continued to increase its production sinusoidally until the late 2010s. Sistan and Baluchestan province exhibited an overall increasing trend in red meat production throughout the entire period, despite experiencing a production drop in the early and mid-2000s. With the exception of a sharp spike in 2004, it has experienced a stable production process with severe fluctuations, meaning that at the end of the 2000s and 2010s, red meat production was nearly identical, yet there were substantial variations in red meat production throughout this period. Fars province has also experienced a proportional trend in red meat production; however, this trend peaked in the mid-2010s before indicating a decline in production. Moreover, this parabolic trend has been accompanied by fluctuations throughout its entire course. Qazvin province has experienced a very gentle, non-fluctuating upward trend in red meat production during the 2000s and 2010s. Of course, this trend had a steeper slope in the mid-2000s compared to other years. Nevertheless, the main characteristic of red meat production in Qazvin province is its minimal fluctuations, indicating that uncertainties in red meat production have been very low over these two decades. Until the mid-2010s, Qom province exhibited a red meat production process resembling a descending step function, meaning it experienced alternating periods of production decline and stability. However, since the mid-2010s, red meat production in this province has increased at a relatively rapid pace.

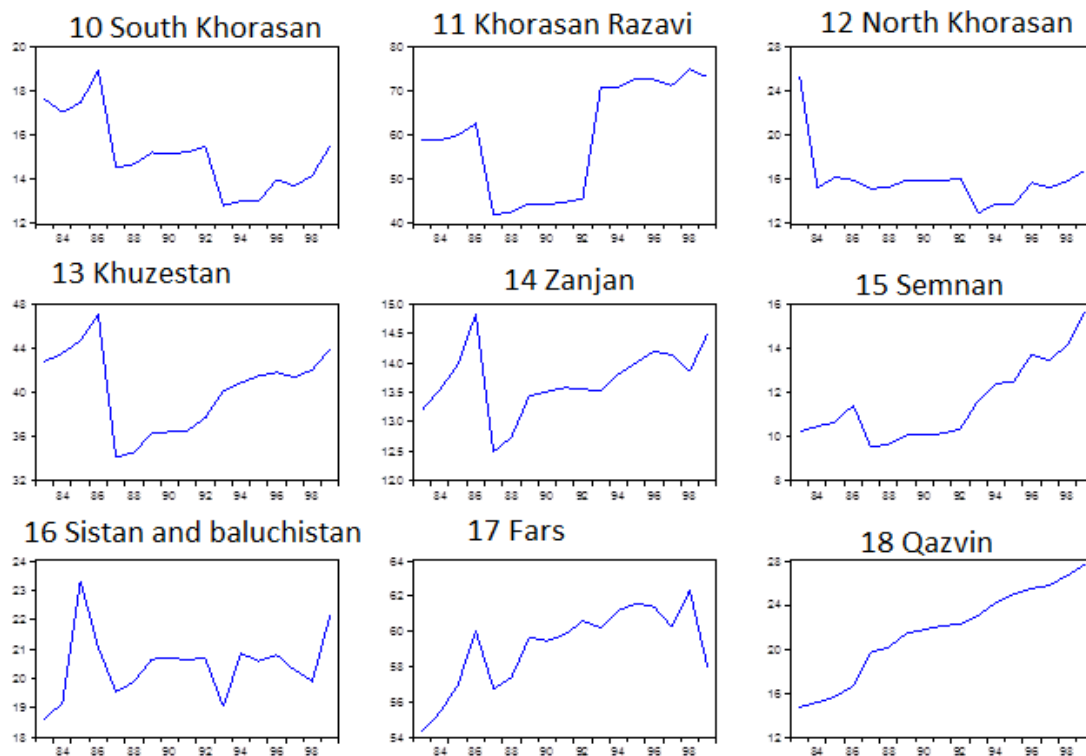


Figure 2. Red meat production chart for each province of the country (second category)

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Red meat production in Kurdistan province at the end of the 2010s differs little from the early 2000s. However, when examining the year-to-year changes in production, it becomes evident that production fluctuations during this period have been highly severe; for instance, production experienced a drastic spike in 2005, but subsequently stabilized at a comparable level following a decline. The volume of red meat production in Kerman province has remained at a constant level following a severe drop in the early 2000s, exhibiting minimal changes until the late 2010s. Consequently, over this 15-year period, the level of red meat production in the province has been highly stable with negligible fluctuations. In Kermanshah province, the trend of red meat production has been upward during the 2000s and 2010s; however, this trend exhibits a sinusoidal pattern, and the amplitude of the maximum and minimum fluctuations of the sinusoidal wave is decreasing over time. In this regard, the effect of production uncertainty on red meat production in Kermanshah province is on the decline, which heralds a more stable production trend. In Kohgiluyeh and Boyer-Ahmad province, red meat production was on an upward trajectory until the mid-2000s; subsequently, this production stabilized at a lower level following a severe drop, after which a very gentle upward trend with minimal fluctuations in red meat production is observed. Red meat production in Golestan province has attempted to maintain its upward trend but faced a severe decline in the mid-2000s before striving to return to its ascending trajectory. From 2008 until the end of the 2010s, the red meat production trend in this province has experienced a slight increase with minor fluctuations. Red meat production in Gilan province has experienced a long-term downward trend from the early 2000s to the late 2010s. This downward trend is attributed to a severe reduction in red meat production in the mid-2000s. Thereafter, it remained relatively stable; however, examining the year-to-year changes in production reveals a sinusoidal movement in the volume of red meat production.

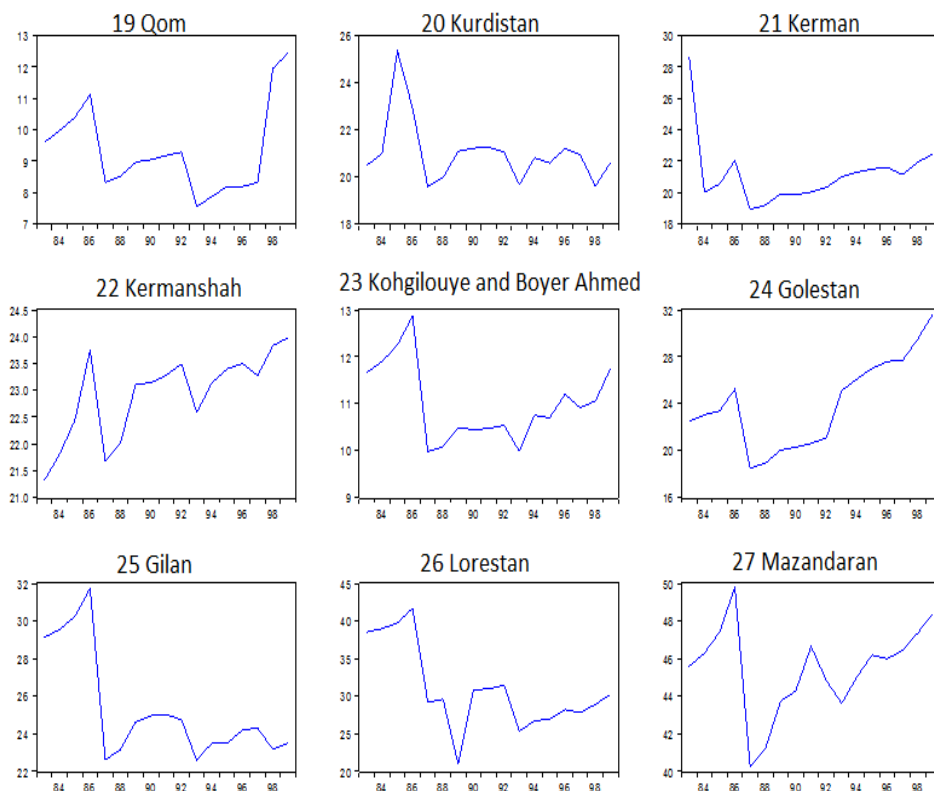


Figure 3. Red meat production chart for each province of the country (third category)

The long-term trend of red meat production in Lorestan province during the 2000s and 2010s has been downward; however, this declining trajectory has been accompanied by severe fluctuations. Specifically, in the second half of the 2000s, red meat production suddenly halved, experiencing a drastic decline, before stabilizing with a slight increase by the end of the decade. Nevertheless, overall, red meat production in this province has exhibited a long-term downward trend. Over the 20-year period spanning the 2000s and 2010s, the volume of red meat production in Mazandaran province has undergone minimal net change, meaning the production level at the end of the 2010s remained comparable to that at the beginning of the 2000s. Production fluctuations during this timeframe have been substantial and sinusoidal in shape. Nevertheless, the wavelength of these sinusoidal movements and the distance between peaks and troughs have gradually decreased over time, ultimately revealing slight evidence of production growth in the province by the late 2010s. Red meat production in Markazi province resembles a parabolic curve, indicating that production faced a severe drop in the mid-2000s before assuming an upward trajectory. This upward trend has a gentler slope compared to the severe decline in the late 2000s; however, comparing production in the early 2000s with that of the late 2010s reveals no significant increase in the volume of red meat production. Over the long-term period of the 2000s and 2010s, red meat production in Hormozgan has exhibited a very gentle trend. This mild increase in production, framed within a parabolic curve, can be understood by its maximum point occurring in the 2010s, particularly in the early 2010s. This implies that red meat production faced a sharp increase from the mid-2000s, peaked by the mid-2010s, and ultimately experienced a decline in 2020, stabilizing at a certain level, which yields a parabolic shape with a distinct maximum point. The trend of red meat production in Hamedan province has shown a slight increase over the long-term period from the early 2000s to the end of the 2010s. This trend experienced a decline in the mid-2000s, specifically undergoing a severe drop in 2006, before resuming a gentle upward trajectory.

Red meat production in Yazd province has exhibited an increasing trend with a relatively steeper slope compared to other provinces across the country. This upward trajectory has been accompanied by relatively sinusoidal movements with long wavelengths; however, the disparity between the maximum and minimum values is negligible. Currently, this minimal fluctuation indicates the high stability of red meat production in Yazd province. Conversely, red meat production in the southern region of Kerman, including Jiroft and Kahnuj, has followed a trend contrary to that of other provinces. Specifically, while the overall trend has been increasing over the 2000s and 2010s, the primary spike in the province's red meat production occurred in the late 2000s, and no such surge has been observed since then throughout the entire 2010s. Significant shifts have occurred in the production level, albeit with minor fluctuations.

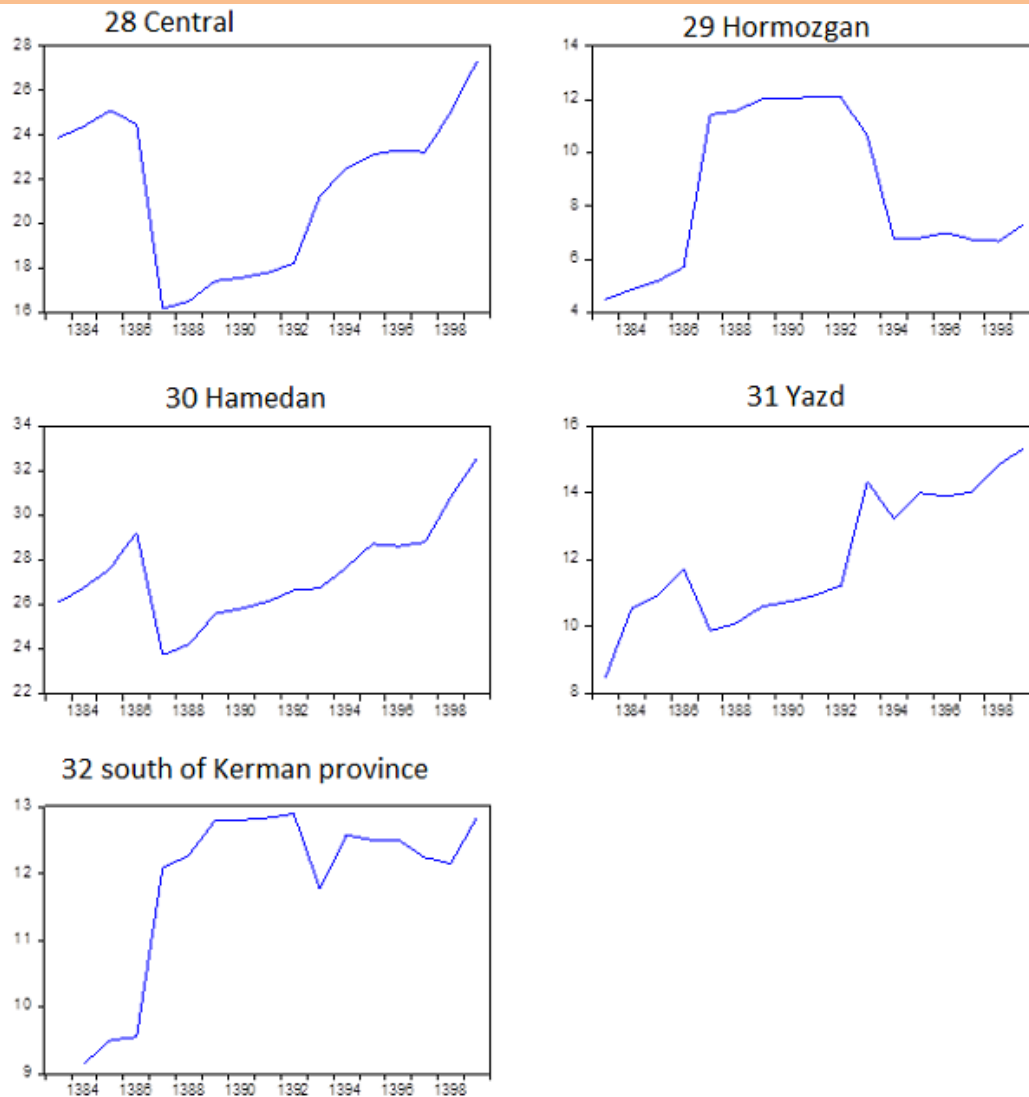


Figure 4. Red meat production chart for each province of the country (fourth category)

Red meat production in Yazd province has exhibited an increasing trend with a relatively steeper slope compared to other provinces across the country. This upward trajectory has been accompanied by relatively sinusoidal movements with long wavelengths; however, the disparity between the maximum and minimum values is negligible. Currently, this minimal fluctuation indicates the high stability of red meat production in Yazd province. Conversely, red meat production in the southern region of Kerman, including Jiroft and Kahnuj, has followed a trend contrary to that of other provinces. Specifically, while the overall trend has been increasing over the 2000s and 2010s, the primary spike in the province's red meat production occurred in the late 2000s, and no such surge has been observed since then throughout the entire 2010s. Significant shifts have occurred in the production level, albeit with minor fluctuations.

Theoretical Model of the Study

In this section, we present the theoretical model of the study. We consider the maximum likelihood (ML) estimation of the following normal-half-normal stochastic frontier (SF) model:

$$\begin{aligned}
 y_{it} &= \alpha + \mathbf{x}'_{it}\beta + \varepsilon_{it}, \quad i = 1, \dots, N, \quad t = 1, \dots, T_i \\
 \varepsilon_{it} &= v_{it} - u_i \\
 v_{it} &\sim \mathcal{N}(0, \sigma_v^2) \\
 u_i &\sim \mathcal{N}^+(0, \sigma_u^2)
 \end{aligned}$$

The generalization of this model to the normal-truncated normal model was proposed by Battese and Coelli (1988). As noted by Schmidt and Sickles (1984), estimating an SF model with a time-invariant inefficiency term can also be achieved by adapting conventional fixed-effects estimation techniques, which in turn allows inefficiency to be correlated with the explanatory variables. However, the time-invariant nature of the inefficiency term has been called into question, particularly for empirical applications based on long panel datasets. To address this limitation, Cornwell, Schmidt, and Sickles (1990) resolved the issue by proposing the following SF model with slope-specific parameters:

$$\begin{aligned}
 y_{it} &= \alpha + \mathbf{x}'_{it}\beta + v_{it} \pm u_{it}, \quad i = 1, \dots, N, \quad t = 1, \dots, T_i \\
 u_{it} &= \omega_i + \omega_{i1}t + \omega_{i2}t^2
 \end{aligned}$$

where the coefficients are estimated using conventional panel data estimators with fixed and random effects. This quadratic specification allows for a unit-specific temporal pattern of inefficiency, but it requires the estimation of a large number of parameters ($N \times 3$). Pursuing a slightly different estimation strategy, Lee and Schmidt (1993) proposed an alternative specification in which the inefficiency term is specified as follows:

$$u_{it} = g(t) \times u_i$$

where $g(t)$ is represented by a set of time dummy variables. This specification is more parsimonious than the previous one and does not impose any parametric form; however, it is less flexible as it imposes a common temporal pattern that must be identical for all production units. Kumbhakar (1990) proposed the maximum likelihood (ML) estimation of a time-varying SF model in which $g(t)$ is specified as:

$$g(t) = \{1 + \exp(\gamma t + \delta t^2)\}^{-1}$$

This model includes only two additional parameters to be estimated, namely γ and δ , and the hypothesis of time-invariant technical efficiency can be easily tested by setting $\gamma = \delta = 0$.

Model Estimation

The objective of this section is to estimate the empirical model of this study. As mentioned above, our primary goal is to estimate time-varying inefficiency in the production function

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while disentangling it from the unobserved cross-sectional heterogeneity over time. To this end, the model variables are defined as follows:

lm = the natural logarithm of red meat production (in million tons),

lf = the natural logarithm of forage input used in the provinces,

lgos = the natural logarithm of the provincial sheep and goat population,

lgav = the natural logarithm of the provincial cattle and calf population.

Based on the panel unit root tests, all variables are stationary. Accordingly, the Cobb-Douglas production function is estimated with red meat production as the dependent variable. The software output is as follows:

Table 1. Stata software output

```

True random-effects model (exponential)           Number of obs =      413
Group variable: var01                             Number of groups =    32
Time variable: id01                               Obs per group: min =   10
                                                    avg =      12.9
                                                    max =      13

                                                    Prob > chi2 =      0.0000
Log simulated-likelihood = 227.0083                Wald chi2(3) =      195.61

Number of Pseudo Random Draws = 100

```

	lm	Coef.	Std. Err.	z	P> z	[95% Conf. Interval]
Frontier						
	lf	.0244514	.004696	5.21	0.000	.0152475 .0336553
	lgav	.2041759	.0267435	7.63	0.000	.1517596 .2565923
	lgos	.2853535	.0246398	11.58	0.000	.2370605 .3336466
	_cons	-.3940619	.2693847	-1.46	0.144	-.9220461 .1339223
Usigma						
	_cons	-5.372489	.3158311	-17.01	0.000	-5.991506 -4.753471
Vsigma						
	_cons	-4.663963	.143664	-32.46	0.000	-4.945539 -4.382387
Theta						
	_cons	.2624664	.0234204	11.21	0.000	.2165632 .3083696
	sigma_u	.0681364	.0107598	6.33	0.000	.0499999 .0928532
	sigma_v	.0971031	.0069751	13.92	0.000	.0843509 .1117833
	lambda	.7016905	.0162854	43.09	0.000	.6697717 .7336093

As observed, the logarithm of forage consumption has a positive and significant effect on red meat production, with a coefficient of 0.02; in other words, the production elasticity with respect to livestock forage consumption in the provinces is 0.02. The cattle and calf population

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exerts a positive influence on annual red meat production, and the production elasticity with respect to this variable is 0.2. This effect is also statistically significant. The production elasticity of red meat with respect to the provincial sheep and goat population is 0.3 and is significant; therefore, the highest production elasticity among the inputs pertains to the sheep and goat population in the provinces.

Furthermore, as observed, the estimated standard deviation of the inefficiency term is 0.07 and is statistically significant, indicating that production suffers from technical inefficiency. The estimated standard deviation of the error term is also approximately 0.1, which is significant. Finally, the ratio of the estimated standard deviation of the inefficiency term to the estimated standard deviation of the model's error term is 0.7, which is statistically significant.

Testing the Research Hypotheses

As expected, one of the research hypotheses is that a model incorporating unobserved heterogeneity in the production function outperforms the simple frontier model for estimating inefficiency, and that the proposed model yields superior estimation results regarding red meat production conditions and its inefficiency. To this end, and to test this hypothesis, a conventional frontier model was estimated using Stata software, utilizing the same production inputs for red meat production. The software output for the conventional model, which does not account for time-varying inefficiency, is as follows:

Table 2. Stata software output

Time-invariant inefficiency model		Number of obs	=	413		
Group variable: var01		Number of groups	=	32		
		Obs per group: min	=	10		
		avg	=	12.9		
		max	=	13		
		Wald chi2(3)	=	117.81		
Log likelihood = 219.04194		Prob > chi2	=	0.0000		
lm	Coef.	Std. Err.	z	P> z	[95% Conf. Interval]	
lf	.026042	.0056214	4.63	0.000	.0150243	.0370596
lgav	.225527	.0260442	8.66	0.000	.1744814	.2765727
lgos	.2204969	.0377233	5.85	0.000	.1465606	.2944333
_cons	.5051823	.3953887	1.28	0.201	-.2697653	1.28013
/mu	.5917233	.1113659	5.31	0.000	.3734502	.8099965
/lnsigma2	-2.204603	.32024	-6.88	0.000	-2.832262	-1.576944
/ilgtgamma	1.884942	.3842308	4.91	0.000	1.131863	2.63802
sigma2	.1102943	.0353206			.0588795	.2066055
gamma	.8681777	.0439734			.7561826	.9332688
sigma_u2	.095755	.0354111			.0263506	.1651595
sigma_v2	.0145392	.0010735			.0124353	.0166432

Based on this output, the Wald statistic for the model accounting for unobserved heterogeneity is approximately 195, whereas for the model without accounting for this unobserved heterogeneity, the Wald statistic is approximately 117. Although the p-value for this statistic is below 5% in both models, it is evident that the numerical value of the statistic is higher for the model incorporating heterogeneity. This statistic indicates the goodness of fit of the model; the higher its value, the more strongly the null hypothesis of model insignificance is rejected. Specifically, given that the corresponding p-value is below 5%, the null hypothesis—indicating the insignificance of the model—is rejected, implying that the independent variables exert a significant effect on the dependent variable. As stated and observed, the value of the Wald test statistic is larger for the model that accounts for unobserved heterogeneity. Consequently, the aforementioned hypothesis, which posits that the model incorporating unobserved heterogeneity is more appropriate, is confirmed. Therefore, in contrast to the conventional model, it is recommended to employ a model that accounts for unobserved heterogeneity. Specifically, the estimated model incorporates unobserved heterogeneity of the random effects type; thus, it is recommended to utilize such a model in efficiency and inefficiency studies pertaining to red meat production, and to calculate efficiency scores based on this model.

Estimation of Provincial Inefficiency in Red Meat Production

In this section, we proceed to analyze the inefficiencies in red meat production. As stated at the beginning of the paper, the advantage of the current model is its ability to estimate cross-sectional inefficiency while accommodating its variation over time. In this regard, the figures for the inefficiency variable over time across the provinces have been calculated, and based on the estimated model, these figures can now be interpreted as follows:

Over the period from the 2000s to 2021, the inefficiency in red meat production in East Azerbaijan province has exhibited a more or less uniform downward pattern. This implies that the efficiency of red meat production in this province has been on the rise. In West Azerbaijan province, a decreasing trend in red meat production inefficiency can be observed, with the difference that in the mid-2010s, the inefficiency experienced an upward spike before ultimately returning to a downward trajectory. In Ardabil province, a decreasing trend in red meat production inefficiency is observed during the 2000s and 2010s; however, the fluctuations in this inefficiency have been substantial, accompanied by numerous ups and downs. In Isfahan province, the inefficiency in red meat production has been continuously decreasing, exhibiting a long-term downward trend. In Alborz province, inefficiency has been declining over the past years, indicating an increase in production efficiency within the province. In this province, an increasing trend in inefficiency is also observed, which exhibited a very severe spike in the mid-2010s.

In Bushehr province, inefficiency exhibits a very steep downward slope, indicating that the efficiency of red meat production in this province has been on the rise throughout the 2000s and 2010s. In Tehran province, the efficiency of red meat production has been increasing over the 2000s and 2010s; although a temporary decline is observed in the early 2010s, overall inefficiency in the province has been decreasing over time. In Chaharmahal and Bakhtiari province, red meat production inefficiency has experienced substantial fluctuations throughout the 2000s and 2010s, exhibiting a very gentle upward trend. In South Khorasan province, red meat production inefficiency generally follows a downward trend, albeit accompanied by high

fluctuations. In Razavi Khorasan province, fluctuations in red meat production inefficiency have been substantial; however, overall, it has exhibited a downward trend during the 2000s and 2010s. In North Khorasan province, the efficiency of red meat production has been steadily increasing, and the corresponding inefficiency has been declining, with minimal fluctuations in this inefficiency.

Red meat production inefficiency in Khuzestan province exhibits a very steep downward slope, indicating that production efficiency in this province has been increasing over time. In Zanjan province, until the end of the 2000s, the efficiency of red meat production increased at a very steep rate, accompanied by a drastic drop in inefficiency; however, since the early 2010s, it has remained at a relatively constant level, with no significant changes observed in efficiency. In Semnan province, the efficiency of red meat production has been on the rise, continuing its upward trajectory with a sharp increase at the beginning of the 2010s. In Sistan and Baluchestan province, although there were fluctuations in red meat production inefficiency during the 2000s, characterized by numerous ups and downs, ultimately, with the onset of the 2010s, this inefficiency began to decline and appears to have stabilized. In Fars province, red meat production inefficiency suffers from severe fluctuations and exhibits a slow decline in the long term. In Qazvin province, red meat production inefficiency has not shown any significant change over time; it declined for ten years, was subsequently followed by an increase, and ultimately reached a constant figure over the entire period. Such inefficiency is evident in this province.

In Qom province, no significant decrease in inefficiency was observed until the end of 2006. From 2008 to 2013, red meat production inefficiency decreased slightly; however, with the onset of the 2010s, the efficiency of red meat production increased sharply, and ultimately, by the end of the 2010s, this inefficiency remained at a constant level. In Kurdistan province, the reduction in red meat production inefficiency has been very slow, exhibiting a downward trend in the long run. In Kerman province, no significant change in efficiency is observed throughout the entire period of the 2000s and 2010s; however, between the 2000s and 2010s, this inefficiency was accompanied by a slight increase. In Kermanshah province, inefficiency increased until the early 2010s and was subsequently eliminated.

Inefficiency Scores of the Country's Provinces

In this section, we examine the ranking of the provinces in terms of inefficiency in red meat production. Based on the inefficiency figures for the provinces during the 2000s and 2010s, the average inefficiency of the provinces has been calculated. Accordingly, the highest inefficiency in red meat production, in descending order, pertains to the provinces of Ilam, Kurdistan, Kerman, Zanjan, Markazi, Kermanshah, Yazd, Lorestan, Kohgiluyeh and Boyer-Ahmad, Khuzestan, Gilan, Hamedan, Qazvin, Ardabil, Semnan, Sistan and Baluchestan, South Khorasan, North Khorasan, the southern region of Kerman province including Jiroft and Kahnuj, West Azerbaijan, Bushehr, Qom, Fars, Chaharmahal and Bakhtiari, Isfahan, and Hormozgan. Therefore, if we are to rank the most inefficient provinces from 1 to 3, these provinces are Ilam, Kurdistan, and Kerman. If we are to identify the three most efficient provinces in red meat production, they are Razavi Khorasan, Golestan, and Tehran.

In the next step, the trend of changes in the efficiency and inefficiency of red meat production across the country's provinces can be examined. The causes of these changes can be attributed to three domains: the agricultural sector, inter-sectoral changes, and macro-level national changes. This means that changes in the agricultural sector policies of the province, the interaction between the agricultural and industrial sectors with other sectors, or macro-level national developments can lead to these changes. What this analysis reveals is that red meat production inefficiency has decreased in most provinces during the 2000s and 2010s. The provinces that have experienced a continuous decrease in red meat production inefficiency include Khuzestan, Zanjan, Sistan and Baluchestan, East Azerbaijan, Alborz, Isfahan, Bushehr, Tehran, and North Khorasan. On the other hand, several provinces have exhibited an increasing trend in inefficiency changes, among which are Semnan and Chaharmahal and Bakhtiari. A few provinces experienced a very negligible decrease in inefficiency or changes in inefficiency in the early 2000s.

5. Conclusion

Stochastic frontier models, traditionally used to estimate inefficiency scores in production, suffer from two fundamental shortcomings. These models attempt to estimate the production possibility frontier in the form of a production function using observed production inputs, and then identify inefficient units or cross-sections as those observations lying below this frontier. However, these studies calculated the resulting inefficiency in the form of time-invariant scores, whereas it is well established that in the long run, inefficiency varies over time due to differing provincial conditions and organizational policies. Consequently, an attempt was made to propose a model that not only calculates the estimated inefficiency as time-varying but also properly accounts for inter-provincial differences, which manifest as cross-sectional heterogeneity in panel data. This model was estimated and compared with previous models that suffered from these two issues, and its superiority was confirmed through the Wald test. Subsequently, the inefficiency scores of the provinces were calculated, the trend of this inefficiency variable over time was analyzed for each province, and the provinces were ranked in terms of the most and least efficient. Therefore, if we are to identify the three most inefficient provinces, they are Ilam, Kurdistan, and Kerman. If we are to name the three most efficient provinces in terms of red meat production, they are Razavi Khorasan, Golestan, and Tehran. The provinces that have experienced a continuous decrease in red meat production inefficiency include Khuzestan, Zanjan, Sistan and Baluchestan, East Azerbaijan, Alborz, Isfahan, Bushehr, Tehran, and North Khorasan. On the other hand, several provinces have exhibited an increasing trend in inefficiency changes, among which are Semnan and Chaharmahal and Bakhtiari. A few provinces have experienced a very negligible decrease in inefficiency or changes in inefficiency during the 2000s and 2010s.

Given the research findings and the limitations of the country's natural resources and rangelands, the following recommendations are provided to the policymakers of the Ministry of Jihad Agriculture and provincial organizations to enhance the efficiency of the livestock sector:

Shifting the approach from quantitative to qualitative development in inefficient provinces: Given the high inefficiency in Ilam, Kurdistan, and Kerman provinces, it is recommended that

development policies in these regions shift their focus from a "quantitative increase in livestock population" to "enhancing productivity and herd management." Providing government incentives for modernizing traditional livestock farms, improving livestock breeds, and establishing scientific fattening systems in these provinces should be prioritized.

Optimal management of forage inputs: The very low production elasticity with respect to forage inputs indicates that merely increasing the quantity of feed inputs does not lead to a proportional increase in production. Therefore, instead of general subsidies for input purchases, policymakers should focus on improving forage "quality," developing high-density and low-water-demand crops, and training livestock farmers in scientific ration formulation to prevent the waste of forage resources.

Local diagnostic assessment in provinces with an increasing inefficiency trend: For provinces that have experienced increased inefficiency during the study period (Semnan and Chaharmahal and Bakhtiari), conducting a precise local diagnostic assessment is essential. It appears that climate change, successive droughts, and the reduction of rangeland areas in these provinces have negatively affected efficiency; thus, revising water allocation policies and developing confined livestock systems (as rangeland alternatives) in these regions is inevitable. **Benchmarking and technology transfer from efficient provinces:** Razavi Khorasan, Golestan, and Tehran provinces have been able to approach the efficiency frontier due to better access to infrastructure, markets, and veterinary services. Expanding extension services, creating modern livestock clusters, and transferring the managerial experiences of these provinces to other parts of the country can reduce the inter-provincial efficiency gap.

Ultimately, it must be emphasized that under the country's current conditions, which are characterized by severe limitations in water and rangeland resources, enhancing technical efficiency through optimal input management and the adoption of modern livestock technologies is not only a vital solution for increasing red meat production and ensuring food security but also a necessary step toward realizing sustainable agriculture and preserving the environmental ecosystem.

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ACKNOWLEDGMENTS

The current study has not received any grant, fund or contribution from private or government institutions. Also, the authors declare that there is no conflict of interests

ETHICAL CONSIDERATION

Authenticity of the texts, honesty and fidelity has been observed.

CONFLICT OF INTEREST

Author/s confirmed no conflict of interest.