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Efficiency of agricultural and pastoral systems in China considering shared factors and undesirable outputs

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Abstract: Assessing and optimising the efficiency of agricultural and pastoral systems is crucial for the long-term development of a country. The presence of shared factors and undesirable outputs increases the complexity of evaluating the efficiency of these systems. To address this issue, we first analysed the production possibility sets of the agricultural subsystems, pastoral subsystems, and agricultural and pastoral systems. Then, two bounded adjusted measure (BAM) models considering shared factors and undesirable outputs were proposed to evaluate the divisional efficiency of agricultural and pastoral subsystems. Additionally, a network BAM model in the presence of shared factors and undesirable outputs was developed to assess overall efficiency. Undesirable outputs were handled by slack-based measures in the three novel models. The proposed models were used to evaluate the efficiency of agricultural and pastoral systems across 30 provinces and cities in China. To explore the impact of undesirable outputs, the efficiency of ignoring undesirable outputs was investigated and compared with that obtained from the new method. These results suggest that ignoring undesirable outputs may misestimate efficiency to a certain extent.

Keywords: agriculture; bounded adjusted measure; data envelopment analysis; shared factors; undesirable outputs

Agriculture and pastoral systems are vital industries that significantly affect the national economy and people's livelihoods. In China, these systems provide employment for nearly 200 million people and sustain approximately 18% of the world's population on approximately 9% of the planet's arable land, according to the World Bank Group. As their production capacity steadily increases, they fundamentally enhance the income for farmers and herders, ensure national food security, and drive rural economic growth. However, the development of agricultural and pastoral systems in China still faces many challenges, such as high consumption and high emissions. To promote green and sustainable development in agricultural and pastoral systems, the national rural revitalisation strategy emphasises the need to comprehensively enhance the efficiency of production, management, and services of agricultural and pastoral systems to achieve agricultural modernisation.

Assessing the efficiency of agricultural and pastoral systems and improving their production efficiency are current research priorities. Evaluating the efficiency of agricultural and pastoral systems poses a challenging question because they are composed of agricultural and pastoral subsystems. Currently, the Data Envelopment Analysis (DEA) technology is an effective meth-

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od for assessing the efficiency of agricultural and pastoral systems. Charnes et al. (1978) introduced the Charnes, Cooper, and Rhodes (CCR) model under the assumption of constant returns to scale (CRS). Banker et al. (1984) developed the Banker, Charnes and Cooper (BCC) model under the variable returns to scale (VRS) condition. Non-radial methods have been presented along with the development of DEA technology. For example, Cooper et al. (2011) introduced a new weighted additive model called the bounded adjusted measure (BAM). As a non-radial model, the BAM allows for independent adjustments of each input or output variable, thereby more accurately reflecting the specific sources of efficiency loss. In contrast, radial models, such as CCR and BCC, can only proportionally adjust inputs or outputs and cannot optimise any specific input or output individually.

Practical agricultural and pastoral systems often have two distinct elements: shared factors and undesirable outputs. Shared factors refer to outputs or inputs commonly used across different production processes. Common shared factors include labour, technology, and equipment. Undesirable outputs are outputs that decision makers typically wish to minimise, in contrast to desirable outputs. Common undesirable outputs include CO_2 and wastewater emissions. The presence of these two factors increases the complexity of measuring the efficiency of agricultural and pastoral systems. The proper handling of both shared factors and undesirable outputs is critical for agricultural and pastoral systems as it directly determines the accuracy of efficiency assessments and the rationality of resource optimisation. The existing literature generally overlooks the influence of shared factors for two main reasons: *i*) these elements are inherently difficult to identify and *ii*) they cannot be properly handled with current methodologies. Most existing studies fail to account for the negative impacts of undesirable outputs and consequently adopt inappropriate analytical approaches.

Cooper et al. (2011) mentioned that the BAM method has a stronger capability for identifying decision-making units (DMUs). In addition to possessing all the advantages of non-radial models, the BAM maintains a concise formulation that remains a linear programming model even after incorporating special variables. By contrast, both the slacks-based measure (SBM) and enhanced Russell models (ERM) transform into nonlinear programming models under similar conditions (Tone 2001). Given the superiority of the BAM method, this study proposes a new approach based on the BAM technology to evaluate the efficiency of agricultural and pastoral systems in China, incorporating shared factors and undesirable outputs. The contributions of this study are as follows: *i*) we establish BAM models with shared factors and undesirable outputs to evaluate the efficiency of agricultural and pastoral subsystems; *ii*) an overall efficiency BAM is proposed to assess the efficiency of agricultural and pastoral systems; and *iii*) our new method is used to measure the efficiency of agricultural and pastoral systems in China, which provides more precise guidance for actual production.

The remainder of this paper is organised as follows: Section 2 summarises the existing literature from three perspectives: agriculture and pastoral systems, shared factors, and undesirable outputs. Section 3 analyses the production possibility sets (PPS) involving shared factors and undesirable outputs in the agricultural and pastoral systems. It then proposes a BAM that considers these factors, along with divisional efficiency models. Section 4 applies the novel method to assess the efficiency of agricultural and pastoral systems across 30 Chinese provinces and cities. Section 5 explores efficiency that ignores undesirable outputs. Section 6 concludes the study.

Literature review

Agriculture and pastoral systems. Currently, research evaluating the efficiency of agricultural and pastoral systems is limited. Wagan et al. (2018) used the DEA method to evaluate and compare agricultural production efficiency between China and Pakistan. Nandy et al. (2021) estimated the efficiency of rice producers in eastern rural India using a fuzzy DEA method. Chen et al. (2021b) employed a three-stage slacks-based measurement method that incorporated undesirable outputs to evaluate the total factor productivity of agriculture across 30 provinces in China. Manogna and Aswini (2022) conducted an efficiency assessment of grain agricultural productivity in 20 states of India using the CCR model and Malmquist productivity index.

However, existing studies on the efficiency of agricultural and pastoral systems mostly utilise traditional radial DEA methods and neglect non-radial models. In addition, the shared and undesirable factors have been overlooked. Furthermore, most researchers have only focused on the efficiency of the agricultural subsystem, thereby overlooking the impact of the pastoral subsystem, which is a current deficiency in research.

Shared factors. Current research on shared elements mostly focuses on shared inputs and rarely considers shared outputs. For example, Zhu et al. (2017)

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developed a two-stage network DEA model in the presence of shared inputs based on radial models. Shabani and Akbarpour (2024) proposed a mixed-integer DEA model to assess the performance of a dynamic network in the presence of cross- and serial-shared resources. Wang et al. (2022) proposed cooperative and noncooperative two-stage DEA models in the presence of shared factors to measure the efficiency of regional high-tech industries in China. Zhao et al. (2022) proposed a two-stage network DEA model that considered shared inputs to assess the efficiency of universities' scientific and technological activities in China. Chen et al. (2021a) developed a three-stage super-efficiency DEA model that considered shared inputs and undesirable outputs to evaluate the efficiency of green R&D innovation in the Chinese high-tech industry. Zhang et al. (2021) applied a two-stage network DEA model that considers shared inputs to measure the efficiency of regional innovation in China. He and Zhu (2023) constructed a dynamic two-stage slack-based measurement model with shared inputs to measure the operating efficiency of China's provincial industrial systems.

In addition to neglecting the impact of shared inputs, these studies predominantly adopted radial models and overlooked the advantages of non-radial models. Based on the shortcomings of existing literature, this study proposes a non-radial DEA model that simultaneously considers shared inputs, shared desirable outputs, and shared undesirable outputs to evaluate the efficiency of agricultural and pastoral systems, thereby addressing the gaps in these studies.

Undesirable outputs. In existing DEA research, there are two main methods for handling undesirable outputs: indirect and direct.

For indirect approaches, Scheel (2001) mentioned that there are three methods included in indirect approaches: incorporating undesirable outputs based on the additive inverse, incorporating undesirable outputs as inputs, and adding a sufficiently large number to the additive inverse of the undesirable output such that the resulting output values are positive. Liu et al. (2010) believed that it is beneficial to treat undesirable outputs as desirable inputs. Izadikhah and Khoshroo (2018) proposed a modified ERM that considers undesirable outputs as inputs.

Direct methods, including the slacks-based measure and directional distance function, are widely applied in the DEA field. For example, Färe et al. (2004) presented an environmental performance index based on a distance function, in which undesirable outputs were considered. Chen et al. (2019) proposed a RAM safe traffic efficiency model to measure the performance of truck restriction policies in China by employing a slack-based measure to handle undesirable outputs. Chen et al. (2020) proposed a unified BAM considering undesirable outputs to assess the eco-performance of China's transportation sector. Zhou et al. (2007) employed a distance function to handle undesirable outputs and established a non-radial Malmquist environmental performance index to assess improvements in environmental efficiency across different countries.

The advantage of a slack-based measure is its ability to observe deviations of undesirable outputs from their target levels and simultaneously maximise desirable outputs while minimising undesirable outputs. Therefore, this method has been widely used.

MATERIAL AND METHODS

Production possibility sets

Agricultural and pastoral systems often exhibit parallel structures. Figure 1 illustrates the production processes of the agricultural and pastoral systems.

Assume there are *n* DMUs. Each $DMU^j (j=1,...,n)$ consists of an agricultural subsystem and a pastoral subsystem. $x_{1i}^j (i=1,...,I_1)$ denotes the i^{th} input in the agricultural subsystem. $y_{1r}^j (r=1,...,S_1)$ denotes the r^{th} desirable output in the agricultural subsystem. $b_{1c}^j (c=1,...,C_1)$ denotes the c^{th} undesirable output in the agricultural subsystem. $x_{2i}^j (i=1,...,I_2)$ denotes the i^{th} input in the pastoral subsystem. $y_{2r}^j (r=1,...,S_2)$ denotes the r^{th} desirable output in the pastoral subsystem. $b_{2c}^j (c=1,...,C_2)$ denotes the c^{th} undesirable output in the pastoral subsystem. $x_{i_g}^j (i_g=1,...,I_g)$ denotes the $i_g{}^{\text{th}}$ shared input of the agricultural subsystem and the pastoral subsystem, which serves as an input into both the agricultural subsystem and the pastoral subsystem. $y_{r_g}^j (r_g=1,...,S_g)$ denotes the $r_g{}^{\text{th}}$ shared desirable output of the agricultural subsystem and the pastoral subsystem. $b_{c_g}^j (c_g=1,...,C_g)$ denotes the $c_g{}^{\text{th}}$ shared undesirable output of the agricultural subsystem and the pastoral subsystem.

We now analyse the PPS of the agricultural and pastoral systems. Define the following vectors:.

$$X_1=\left(x_{11},\ldots,x_{1I_1}\right)\in R_+^{I_1} \quad X_2=\left(x_{21},\ldots,x_{2I_2}\right)\in R_+^{I_2}$$

$$Y_1=\left(y_{11},\ldots,y_{1S_1}\right)\in R_+^{S_1} \quad Y_2=\left(y_{21},\ldots,y_{2S_2}\right)\in R_+^{S_2}$$

$$B_1=\left(b_{11},\ldots,b_{1C_1}\right)\in R_+^{C_1} \quad B_2=\left(b_{21},\ldots,b_{2C_2}\right)\in R_+^{C_2}$$

$$X=\left(x_1,\ldots,x_{I_g}\right)\in R_+^{I_g} \quad Y=\left(y_1,\ldots,y_{S_g}\right)\in R_+^{S_g}$$

$$B=\left(b_1,\ldots,b_{C_g}\right)\in R_+^{C_g}$$

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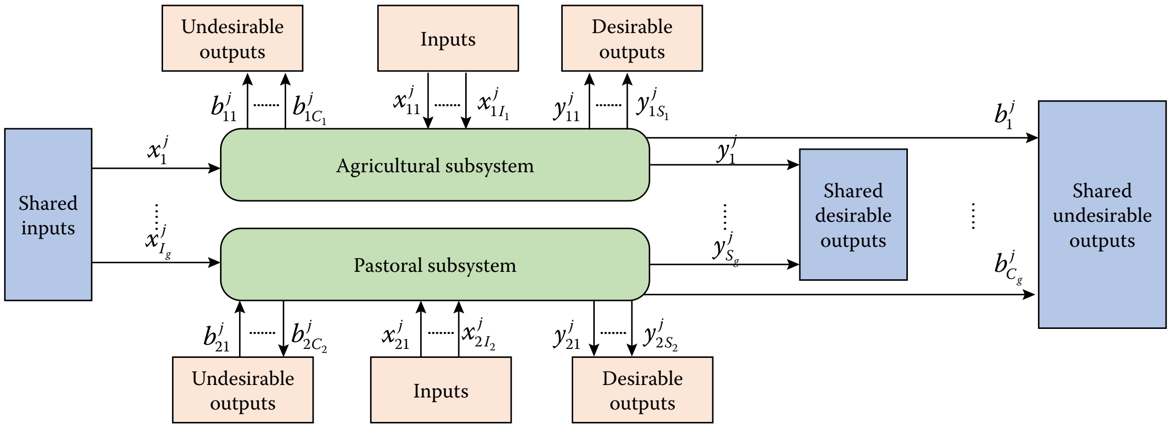

Figure 1. Production process of an agricultural and pastoral system

Source: Compiled by the authors

For the agricultural subsystem, PPS (1) exists.

$$T_1 = \left\{ \begin{array}{c} (X_1,Y_1,B_1,X,Y,B): \sum_{j=1}^{n} \lambda_1^j X_1^j \le X_1, \sum_{j=1}^{n} \lambda_1^j Y_1^j \ge Y_1, \sum_{j=1}^{n} \lambda_1^j B_1^j \le B_1, \sum_{j=1}^{n} \lambda_1^j \mu_{1x} X^j \le \mu_{1x} X, \\ \sum_{j=1}^{n} \lambda_1^j \mu_{1y} Y^j \ge \mu_{1y} Y, \sum_{j=1}^{n} \lambda_1^j \mu_{1b} B^j \le \mu_{1b} B\ , \sum_{j=1}^{n} \lambda_1^j = 1 \end{array} \right\} \quad (1)$$

where: λ_1^j – the intensity of the j^{th} DMU in the agricultural subsystem; μ_{1x} – the proportion of shared inputs allocated to the agricultural subsystems; μ_{1y} – the proportion of shared desirable outputs allocated to the agricultural subsystems; μ_{1b} – the proportion of shared undesirable outputs allocated to the agricultural subsystems; constraint $\sum_{j=1}^{n} \lambda_1^j = 1$ – the VRS assumption.

For the pastoral system, there exists the following PPS (2):

$$T_2 = \left\{ \begin{array}{c} (X_2,Y_2,B_2,X,Y,B): \sum_{j=1}^{n} \lambda_2^j X_2^j \le X_2, \sum_{j=1}^{n} \lambda_2^j Y_2^j \ge Y_2, \sum_{j=1}^{n} \lambda_2^j B_2^j \le B_2, \sum_{j=1}^{n} \lambda_2^j \mu_{2x} X^j \le \mu_{2x} X, \\ \sum_{j=1}^{n} \lambda_2^j \mu_{2y} Y^j \ge \mu_{2y} Y, \sum_{j=1}^{n} \lambda_2^j \mu_{2b} B^j \le \mu_{2b} B, \sum_{j=1}^{n} \lambda_2^j = 1 \end{array} \right\} \quad (2)$$

where: λ_2^j – the intensity of the j^{th} DMU in the pastoral subsystem; μ_{2x}, μ_{2y}, μ_{2b} – the proportion of inputs, desirable outputs, and undesirable outputs allocated to the pastoral subsystem, respectively.

It is worth mentioning that, for PPS (1) and PPS (2), there exist the equations: $\mu_{1x} + \mu_{2x} = 1$, $\mu_{1y} + \mu_{2y} = 1$, $\mu_{1b} + \mu_{2b} = 1$.

Viewing agricultural and pastoral systems as a whole, we obtain PPS (3):

$$T = \left\{ \begin{array}{l} (X_1,Y_1,B_1,X_2,Y_2,B_2,X,Y,B): \\ \sum_{j=1}^{n} \lambda_1^j X_1^j \le X_1, \sum_{j=1}^{n} \lambda_1^j Y_1^j \ge Y_1, \sum_{j=1}^{n} \lambda_1^j B_1^j \le B_1, \sum_{j=1}^{n} \lambda_1^j \mu_{1x} X^j \le \mu_{1x} X\ , \sum_{j=1}^{n} \lambda_1^j \mu_{1y} Y^j \ge \mu_{1y} Y, \\ \sum_{j=1}^{n} \lambda_1^j \mu_{1b} B^j \le \mu_{1b} B\ , \sum_{j=1}^{n} \lambda_1^j = 1, \sum_{j=1}^{n} \lambda_2^j X_2^j \le X_2, \sum_{j=1}^{n} \lambda_2^j Y_2^j \ge Y_2, \sum_{j=1}^{n} \lambda_2^j B_2^j \le B_2, \\ \sum_{j=1}^{n} \lambda_2^j \mu_{2x} X^j \le \mu_{2x} X, \sum_{j=1}^{n} \lambda_2^j \mu_{2y} Y^j \ge \mu_{2y} Y, \sum_{j=1}^{n} \lambda_2^j \mu_{2b} B^j \le \mu_{2b} B, \sum_{j=1}^{n} \lambda_2^j = 1 \end{array} \right\} \quad (3)$$

Divisional efficiency models

According to PPS (1), a BAM model that considers shared factors and undesirable outputs for assessing the efficiency of agricultural subsystems can be proposed [Model (4)].

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$$E_1 = \min \ 1 - \frac{1}{I_1 + S_1 + C_1 + I_g + S_g + C_g}\left(\sum_{i=1}^{I_1}\frac{s_{1i}^-}{B_{1i}^-} + \sum_{r=1}^{S_1}\frac{s_{1r}^+}{B_{1r}^+} + \sum_{c=1}^{C_1}\frac{s_{1c}^-}{B_{1c}^-} + \sum_{i_g=1}^{I_g}\frac{s_{1i_g}^-}{B_{1i_g}^-} + \sum_{r_g=1}^{S_g}\frac{s_{1r_g}^+}{B_{1r_g}^+} + \sum_{c_g=1}^{C_g}\frac{s_{1c_g}^-}{B_{1c_g}^-}\right)$$
$$\begin{aligned}
&s.t.\\
&\sum_{j=1}^{n}\lambda_1^j x_{1i}^j + s_{1i}^- = x_{1i}^o,\ i = 1,2,\ldots,I_1\\
&\sum_{j=1}^{n}\lambda_1^j y_{1r}^j - s_{1r}^+ = y_{1r}^o,\ r = 1,2,\ldots,S_1\\
&\sum_{j=1}^{n}\lambda_1^j b_{1c}^j + s_{1c}^- = b_{1c}^o,\ c = 1,2,\ldots,C_1\\
&\sum_{j=1}^{n}\lambda_1^j \mu_{1i_g} x_{i_g}^j + s_{1i_g}^- = \mu_{1i_g} x_{i_g}^o,\ i_g = 1,2,\ldots,I_g\\
&\sum_{j=1}^{n}\lambda_1^j \mu_{1r_g} y_{r_g}^j - s_{1r_g}^+ = \mu_{1r_g} y_{r_g}^o,\ r_g = 1,2,\ldots,S_g\\
&\sum_{j=1}^{n}\lambda_1^j \mu_{1c_g} b_{c_g}^j + s_{1c_g}^- = \mu_{1c_g} b_{c_g}^o,\ c_g = 1,2,\ldots,C_g\\
&\sum_{j=1}^{n}\lambda_1^j = 1,\ j = 1,2,\ldots,n\\
&s_{1i}^- \geq 0, s_{1r}^+ \geq 0, s_{1c}^- \geq 0, s_{1i_g}^- \geq 0, s_{1r_g}^+ \geq 0, s_{1c_g}^- \geq 0, \lambda_1^j \geq 0
\end{aligned} \tag{4}$$

where: s_{1i}^-, s_{1r}^+, and s_{1c}^-– the slack of inputs, desirable outputs, and undesirable outputs in the agricultural subsystem, respectively; $s_{1i_g}^-$, $s_{1r_g}^+$, and $s_{1c_g}^-$– the slacks of shared inputs, desirable outputs, and undesirable outputs, respectively, in the agricultural subsystem; μ_{1i_g}– the proportion of the i_g^{th} shared input allocated to the agricultural subsystem; μ_{1r_g} – the proportion of the hared desirable output allocated to the agricultural subsystem; μ_{1c_g}– the proportion of the c_g^{th} shared undesirable output allocated to the agricultural subsystem; B_{1i}^-– the lower-side range of the i^{th} input in the agricultural subsystem; B_{1r}^+– the upper range of the r^{th} desirable output in the agricultural subsystem; B_{1c}^-– the lower-side range of the c^{th} undesirable output in the agricultural subsystem; $B_{1i_g}^-$– the lower-side range of the i_g^{th} shared input in the agricultural subsystem; $B_{1r_g}^+$– the upper-side range of the r_g^{th} shared desirable output in the agricultural subsystem; $B_{1c_g}^-$– the lower range of the c_g^{th} shared undesirable output in the agricultural subsystem.

There exist: $B_{1i}^- = x_{1i}^o - \min(x_{1i}^j)$, $B_{1r}^+ = \max(y_{1r}^j) - y_{1r}^o$, $B_{1c}^- = x_{1c}^o - \min(x_{1c}^j)$, $B_{1i_g}^- = \mu_{1i_g} x_{i_g}^o - \min(\mu_{1i_g} x_{i_g}^j)$, $B_{1r_g}^+ = \max(\mu_{1r_g} y_{r_g}^j) - \mu_{1r_g} y_{r_g}^o$, $B_{1c_g}^- = \mu_{1c_g} b_{c_g}^o - \min(\mu_{1c_g} b_{c_g}^j)$.

According to PPS (2), a BAM model that considers shared factors and undesirable outputs to assess the efficiency of the pastoral subsystem can be presented [Model (5)].

$$E_2 = \min \ 1 - \frac{1}{I_2 + S_2 + C_2 + I_g + S_g + C_g}\left(\sum_{i=1}^{I_2}\frac{s_{2i}^-}{B_{2i}^-} + \sum_{r=1}^{S_2}\frac{s_{2r}^+}{B_{2r}^+} + \sum_{c=1}^{C_2}\frac{s_{2c}^-}{B_{2c}^-} + \sum_{i_g=1}^{I_g}\frac{s_{2i_g}^-}{B_{2i_g}^-} + \sum_{r_g=1}^{S_g}\frac{s_{2r_g}^+}{B_{2r_g}^+} + \sum_{c_g=1}^{C_g}\frac{s_{2c_g}^-}{B_{2c_g}^-}\right)$$
$$\begin{aligned}
&s.t.\\
&\sum_{j=1}^{n}\lambda_2^j x_{2i}^j + s_{2i}^- = x_{2i}^o,\ i = 1,2,\ldots,I_2\\
&\sum_{j=1}^{n}\lambda_2^j y_{2r}^j - s_{2r}^+ = y_{2r}^o,\ r = 1,2,\ldots,S_2\\
&\sum_{j=1}^{n}\lambda_2^j b_{2c}^j + s_{2c}^- = b_{2c}^o,\ c = 1,2,\ldots,C_2\\
&\sum_{j=1}^{n}\lambda_2^j \mu_{2i_g} x_{i_g}^j + s_{2i_g}^- = \mu_{2i_g} x_{i_g}^o,\ i_g = 1,2,\ldots,I_g\\
&\sum_{j=1}^{n}\lambda_2^j \mu_{2r_g} y_{r_g}^j - s_{2r_g}^+ = \mu_{2r_g} y_{r_g}^o,\ r_g = 1,2,\ldots,S_g\\
&\sum_{j=1}^{n}\lambda_2^j \mu_{2c_g} b_{c_g}^j + s_{2c_g}^- = \mu_{2c_g} b_{c_g}^o,\ c_g = 1,2,\ldots,C_g\\
&\sum_{j=1}^{n}\lambda_2^j = 1,\ j = 1,2,\ldots,n\\
&s_{2i}^- \geq 0, s_{2r}^+ \geq 0, s_{2c}^- \geq 0, s_{2i_g}^- \geq 0, s_{2r_g}^+ \geq 0, s_{2c_g}^- \geq 0, \lambda_2^j \geq 0
\end{aligned} \tag{5}$$

where: s_{2i}^-, s_{2r}^+, and s_{2c}^- – the slacks of the inputs, desirable outputs, and undesirable outputs in the pastoral subsystem, respectively; s_{2i_g}, $s_{2r_g}^+$, and $s_{2c_g}^-$ – the slacks of shared inputs, desirable outputs, and undesirable outputs in the pastoral subsystem, respectively; μ_{2i_g}– the proportion of the i_g^{th} shared input allocated to the pastoral subsystem; μ_{2r_g} – the proportion of the r_g^{th} shared desirable outputs allocated to the pastoral subsystem; μ_{2c_g}– the proportion of the c_g^{th} shared undesirable output allocated to the pastoral subsystem; B_{2i}^- – the lower-side range of the i^{th} input to the pastoral subsystem; B_{2r}^+ – the upper range of the r^{th} desirable output in the pastoral subsystem; B_{2c}^- – the lower-side

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range of the c^{th} undesirable output in the pastoral subsystem. $B^-_{2i_g}$ – the lower-sided range of the i_g^{th} shared input in the pastoral subsystem; $B^+_{2r_g}$ – the upper-side range of the r_g^{th} shared desirable output in the pastoral subsystem; $B^-_{2c_g}$ – the lower range of the c_g^{th} shared undesirable output in the pastoral subsystem.

There exist: $B^-_{2i} = x^o_{2i} - \min(x^j_{2i})$, $B^+_{2r} = \max(y^j_{2r}) - y^o_{2r}$, $B^-_{2c} = x^o_{2c} - \min(x^j_{2c})$, $B^-_{2i_g} = \mu_{2i_g} x^o_{i_g} - \min(\mu_{2i_g} x^j_{i_g})$, $B^+_{2r_g} = \max(\mu_{2r_g} y^j_{r_g}) - \mu_{2r_g} y^o_{r_g}$, $B^-_{2c_g} = \mu_{2c_g} b^o_{c_g} - \min(\mu_{2c_g} b^j_{c_g})$.

Overall efficiency model

Based on PPS (3), to assess the overall efficiency of agricultural and pastoral systems, we establish a network BAM model with shared factors and undesirable outputs [Model (6)].

$$
\begin{aligned}
&E = \min\ 1 - \sum_p^P \frac{w_p}{I_p + S_p + C_p + I_g + S_g + C_g}\left(\sum_{i=1}^{I_p}\frac{s^-_{pi}}{B^-_{pi}} + \sum_{r=1}^{S_p}\frac{s^+_{pr}}{B^+_{pr}} + \sum_{c=1}^{C_p}\frac{s^-_{pc}}{B^-_{pc}} + \sum_{i_g=1}^{I_g}\frac{s^-_{pi_g}}{B^-_{pi_g}} + \sum_{r_g=1}^{S_g}\frac{s^+_{pr_g}}{B^+_{pr_g}} + \sum_{c_g=1}^{C_g}\frac{s^-_{pc_g}}{B^-_{pc_g}}\right)\\
&s.t.\\
&\sum_{j=1}^{n}\lambda^j_p x^j_{pi} + s^-_{pi} = x^o_{pi},\ i = 1,2,\ldots,I_p\\
&\sum_{j=1}^{n}\lambda^j_p y^j_{pr} - s^+_{pr} = y^o_{pr},\ r = 1,2,\ldots,S_p\\
&\sum_{j=1}^{n}\lambda^j_p b^j_{pc} + s^-_{pc} = b^o_{pc},\ c = 1,2,\ldots,C_p\\
&\sum_{j=1}^{n}\lambda^j_p \mu_{pi_g} x^j_{i_g} + s^-_{pi_g} = \mu_{pi_g} x^o_{i_g},\ i_g = 1,2,\ldots,I_g\\
&\sum_{j=1}^{n}\lambda^j_p \mu_{pr_g} y^j_{r_g} - s^+_{pr_g} = \mu_{pr_g} y^o_{r_g},\ r_g = 1,2,\ldots,S_g\\
&\sum_{j=1}^{n}\lambda^j_p \mu_{pc_g} b^j_{c_g} + s^-_{pc_g} = \mu_{pc_g} b^o_{c_g},\ c_g = 1,2,\ldots,C_g\\
&\sum_{p}^{P}\mu_{pi_g} = 1,\ \sum_{p}^{P}\mu_{pr_g} = 1,\ \sum_{p}^{P}\mu_{pc_g} = 1,\ p \in \{1,2\}\\
&\sum_{j=1}^{n}\lambda^j_p = 1,\ j = 1,2,\ldots,n\\
&s^-_{pi} \geq 0, s^+_{pr} \geq 0, s^-_{pc} \geq 0, s^-_{pi_g} \geq 0, s^+_{pr_g} \geq 0, s^-_{pc_g} \geq 0, \lambda^j_p \geq 0
\end{aligned}
\tag{6}
$$

where: p = 1 – the agricultural subsystem; p = 2 – the pastoral subsystem; s^-_{pi}, s^+_{pr}, and s^-_{pc} – the slack of the inputs, desirable outputs, and undesirable outputs in the p^{th} subsystem, respectively; s_{pi_g}, $s^+_{pr_g}$, and $s^-_{pc_g}$ – the slacks of the shared inputs, desirable outputs, and undesirable outputs in the p^{th} subsystem, respectively; μ_{pi_g} – the proportion of i_g^{th} shared input allocated to the p^{th} subsystem; μ_{pr_g}– the proportion of r_g^{th} shared desirable output allocated to the p^{th} subsystem; μ_{pc_g}– the proportion of c_g^{th} shared undesirable output allocated to the p^{th} subsystem; B^-_{pi} – the lower-side range of the i^{th} input in the p^{th} subsystem; B^+_{pr} – the upper range of the r^{th} desirable output in the p^{th} subsystem; B^-_{pc} – the lower-sided range of the c^{th} undesirable output in the p^{th} subsystem; $B^-_{pi_g}$ – the lower-side range of the i_g^{th} shared input in the p^{th} subsystem; $B^+_{pr_g}$ – the upper-side range of the r_g^{th} shared desirable output in the p^{th} subsystem; $B^-_{pc_g}$ – the lower-sided range of the c_g^{th} shared undesirable output in the p^{th} subsystem; w_p– the weight of the p^{th} subsystem.

It should be noted that w_p reflects the importance of each subsystem. Its value is determined by decision makers based on factors such as the influence and significance of each subsystem.

Data

We collected data on the agricultural and pastoral systems in 30 provinces and cities in China. Figure 2 shows the relevant factors included in agricultural and pastoral systems.

In agricultural subsystems, inputs include total sown area, irrigation water use, fertiliser usage, agricultural plastic film usage, total agricultural machinery power, and pesticide usage. Conversely, desirable outputs include grain production and total agricultural output value. In pastoral subsystems, the input is the number of animals, and desirable outputs include the output of meat, poultry eggs, milk, and the gross output val-

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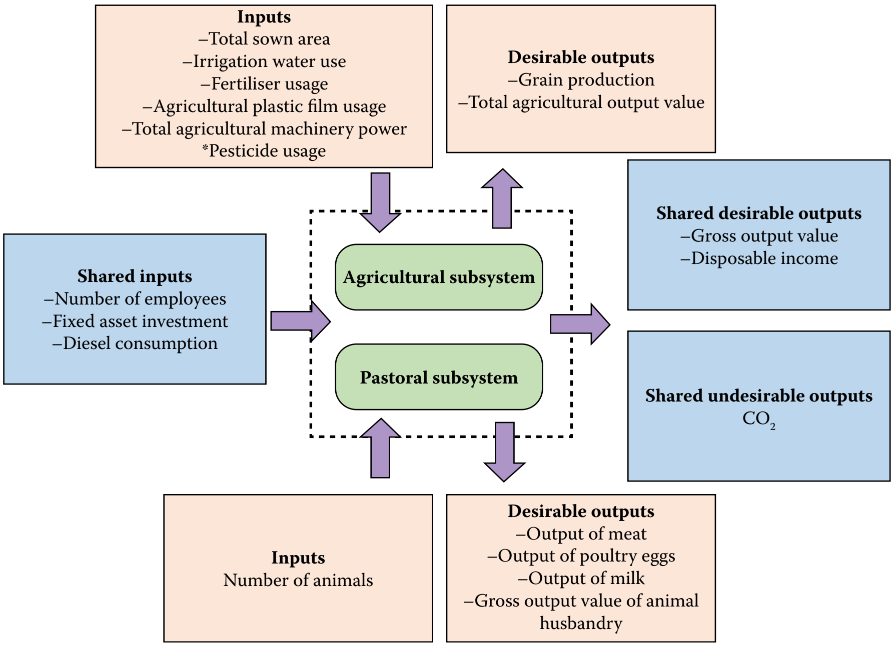

Figure 2. Inputs and outputs in an agricultural and pastoral system

Source: Compiled by the authors

ue of animal husbandry. Shared inputs include the number of employees, fixed asset investments, and diesel consumption. The shared desirable outputs are the gross output value and disposable income. The shared undesirable output is CO_2. Tables 1, 2, and 3 present specific data from the China Statistical Yearbook 2023.

The gross production value of the agricultural subsystems exceeds that of the pastoral subsystems, indicating a greater contribution of agricultural subsystems to national economic development. Therefore, decision makers believe that more shared factors should be allocated to agricultural subsystems. For shared inputs, the proportions allocated to the agricultural subsystems for the number of employees, fixed asset investment, and diesel consumption were 0.65, 0.55, and 0.5, respectively, implying that the proportions allocated to the pastoral subsystems were 0.35, 0.45, and 0.5, respectively. For shared desirable outputs, the proportions of gross output value and disposable income allocated to the agricultural subsystems were 0.7 and 0.75, respectively, while the proportions allocated to the pastoral subsystems were 0.3 and 0.25, respectively. The proportion of the shared undesirable output, that is, CO_2, allocated to the agricultural subsystem was 0.7, which illustrates that the value allocated to the pastoral subsystem was 0.3. For weight w_p, decision-makers allocated a weight of 0.6 to the agricultural subsystems, and a weight of 0.4 to the pastoral subsystems. $w_1 = 0.6$ and $w_2 = 0.4$.

RESULTS

The efficiency of these DMUs was calculated by applying Models (4–6). The results are summarised in Table 4.

From an overall efficiency perspective, 24 DMUs had a production efficiency of one, indicating that they were all efficient. Shanxi, Jilin, Anhui, Guangxi, Shaanxi, and Gansu had efficiency scores of less than 1, indicating that they were all inefficient. Specifically, Gansu had an efficiency of 0.8032, ranking last among the 30 DMUs. This suggests that there are issues with the agricultural and pastoral systems in Gansu that require timely adjustment of production plans.

From the perspective of the agricultural subsystems, there were 3 DMUs that are inefficient. These provinces included Shanxi, Anhui, and Gansu. Among them, Gansu was the poorest-performing DMU with an efficiency score of 0.7695. From the data perspective, for Gansu, the input values were very high, especially for agricultural plastic film usage, with a value of 17.8, ranking third among all DMUs; however, the values of desirable outputs and shared desirable outputs were low. Both factors contributed to lower efficiency. For Anhui and Shanxi, the values of the six inputs among the 30 DMUs were relatively high, but the value of the desirable output is low. This discrepancy contributes to inefficient production.

In terms of pastoral subsystems, 26 DMUs were highly efficient, with efficiency scores of 1. Jilin, Guangxi, Shaanxi, and Gansu were all inefficient. Among them,

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Shaanxi had the lowest efficiency at only 0.8447. Gansu had an efficiency of 0.8537, ranking second to last. Based on the data for Guangxi, the input values were moderate, but the output values were relatively low. The value of shared input (fixed asset investment) was high at 27.46, indicating significant investment. However, the value of poultry eggs was only 13.12, which is at a disadvantage compared with other DMUs. For

Table 1. Data of agricultural subsystems

DMU	Total sown area (10^3 ha)	Irrigation water use (10^3 ha)	Fertiliser usage (10^4 tonnes)	Agricultural plastic film usage (10^4 tonnes)	Total agricultural machinery power (10^4 kw)	Pesticide usage (10^4 tons)	Grain production (10^4 tons)	Total agricultural output value (USD 100 million)
Beijing	143.81	112.14	6.61	0.7	121.14	0.2	45.36	19.29
Tianjin	443.51	293.98	15.52	0.7	370.77	0.2	256.21	41.15
Hebei	8 113.99	4 102.86	271.64	10.1	8 249.08	5.1	3 865.06	600.00
Shanxi	3 611.59	1 502.01	103.47	4.9	1 714.27	2.3	1 464.25	191.55
Inner Mongolia	8 750.68	4 379.31	227.36	11.5	4 596.42	2.5	3 900.63	328.34
Liaoning	4 326.86	1 716.63	130.51	11.3	2 657.84	4.2	2 484.54	335.75
Jilin	6 226.36	1 906.48	222.75	4.6	4 357.86	4.4	4 080.79	224.90
Heilongjiang	15 209.41	6 152.89	238.50	5.8	7 090.88	5.5	7 763.14	642.34
Shanghai	269.17	160.62	6.56	1.2	100.19	0.2	95.57	22.19
Jiangsu	7 534.24	3 851.74	270.14	10.2	5 264.08	6.1	3 769.13	696.65
Zhejiang	2 027.16	1 226.14	67.05	6.9	1 767.56	3.3	620.97	263.13
Anhui	8 933.59	4 576.18	280.19	10.2	7 070.12	7.3	4 100.13	436.66
Fujian	1 682.14	855.47	92.07	4.7	1 296.71	4	508.70	307.11
Jiangxi	5 730.55	2 166.49	107.71	5.4	2 838.16	5.1	2 151.91	284.96
Shandong	10 964.14	5 209.09	362.09	25.4	11 530.49	10.5	5 543.78	922.75
Henan	14 711.51	5 623.22	595.31	14	10 858.66	9.2	6 789.37	1 033.03
Hubei	8 191.92	3 208.84	257.98	5.7	4 878.65	8.5	2 741.15	623.41
Hunan	8 591.54	2 876.00	215.87	7.4	6 755.95	8.2	3 018.02	590.72
Guangdong	4 553.47	1 560.23	208.74	4.5	2 556.30	7.6	1 291.54	640.52
Guangxi	6 271.40	1 549.35	249.2	4.6	3 825.26	6.2	1 393.15	591.38
Hainan	687.18	330.17	38.64	3.5	631.8	1.8	146.58	183.88
Chongqing	3 479.02	669.87	88.74	4.1	1 565.6	1.6	1 072.84	279.77
Sichuan	10 227.36	2 975.74	204.37	11.5	4 923.33	4	3 510.55	821.99
Guizhou	5 359.45	1 185.17	75.41	3.9	2 805.71	0.7	1 114.64	492.66
Yunnan	7 130.63	2 035.26	183.38	11.3	2 913.65	4.1	1 957.96	539.67
Shaanxi	4 212.23	1 161.63	194.16	4.6	2 473.88	1.1	1 297.89	492.17
Gansu	4 061.94	1 349.48	77.13	17.8	2 516.66	2.7	1 264.99	268.57
Qinghai	586.19	222.01	4.71	0.7	503.27	0.1	107.27	35.43
Ningxia	1 189.49	560.57	36.88	2.1	663.43	0.2	375.83	67.73
Xinjiang	6 493.13	6 534.69	243.68	27.9	3 075.35	2	1 813.50	558.12

DMU – decision-making unit
Source: Compiled by the authors based on the China Statistical Yearbook 2023

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Table 2. Data of pastoral subsystems

DMU	Number of animals (10^4 heads)	Output of meat (10^4 tons)	Output of poultry eggs (10^4 tons)	Output of milk (10^4 tons)	Gross output value of animal husbandry (10^4 USD)
Beijing	8.4	4.33	8.73	26.22	6.28
Tianjin	31.1	29.50	20.22	51.13	21.89
Hebei	420.1	478.83	398.44	546.73	355.58
Shanxi	154.1	143.20	117.96	142.80	91.56
Inner Mongolia	956.9	284.05	62.59	733.83	278.96
Liaoning	324.8	446.21	315.83	134.67	251.95
Jilin	401.9	291.04	95.85	29.30	220.42
Heilongjiang	536.2	312.53	107.84	501.15	273.98
Shanghai	5.8	9.54	4.64	30.22	6.89
Jiangsu	28.5	318.06	233.39	68.78	192.41
Zhejiang	15.5	108.49	31.71	19.60	60.31
Anhui	107.2	475.34	186.66	50.74	269.47
Fujian	33.1	296.30	59.83	21.51	158.52
Jiangxi	270.5	359.90	68.37	7.90	162.71
Shandong	287	844.51	438.09	304.40	446.55
Henan	402.9	660.04	456.24	213.17	421.09
Hubei	236.1	441.16	207.96	9.18	316.41
Hunan	443.6	580.86	117.50	7.20	366.76
Guangdong	108.6	481.01	47.20	19.81	249.81
Guangxi	377.3	454.94	29.32	13.12	224.43
Hainan	47	69.20	5.92	0.28	50.62
Chongqing	110.4	205.27	50.50	3.19	119.08
Sichuan	943.9	685.72	175.50	70.80	487.90
Guizhou	505.8	241.03	33.57	3.73	139.96
Yunnan	927	521.60	43.28	69.01	325.94
Shaanxi	154.5	132.09	63.62	107.85	137.59
Gansu	584.7	142.65	21.63	91.83	98.45
Qinghai	660.4	40.98	1.49	35.06	44.95
Ningxia	233.2	36.77	13.21	342.50	48.09
Xinjiang	851.3	204.69	38.22	222.58	194.06

DMU – decision-making unit
Source: Compiled by the authors based on the China Statistical Yearbook 2023

Gansu, the number of animals was 584.7, which was the highest among all DMUs. However, the output value was not correspondingly high. The value of disposable income was 1 808.62, which is the lowest among all the DMUs. These factors contributed to inefficiency in these two provinces.

Overall, the agricultural and pastoral systems of Shanxi, Jilin, Anhui, Guangxi, Shaanxi, and Gansu were inefficient. There seemed to be issues with the production processes of both pastoral and agricultural subsystems. The other DMUs were efficient and perform satisfactorily.

DISCUSSION

The model proposed in this study utilises a slack-based measure to handle undesirable outputs. Undesirable outputs are often overlooked in actual production,

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Table 3. Shared factors

DMU	Number of employees (10^4)	Fixed asset investment (USD 100 million)	Diesel consumption (10^4 tons)	Gross output value (USD 10^4)	Disposable income (USD)	CO_2 (10^4 tons)
Beijing	25	0.13	1.7	25.580	5 167.04	5.30
Tianjin	33	0.22	1.9	63.040	4 314.24	5.90
Hebei	820	4.92	131.6	955.580	2 878.93	409.90
Shanxi	414	5.63	25.2	283.100	2 426.82	78.50
Inner Mongolia	439	17.52	72.4	607.290	2 920.12	225.50
Liaoning	634	24.38	58.3	587.690	2 959.81	181.60
Jilin	479	15.92	61.7	445.320	2 696.06	192.20
Heilongjiang	518	28.33	139.6	916.320	2 761.92	434.90
Shanghai	21	0.03	3	29.083	5 906.69	9.30
Jiangsu	626	7.83	101.3	889.050	4 235.14	315.50
Zhejiang	203	26.07	171.4	323.440	5 584.96	533.90
Anhui	790	13.38	73.8	706.140	2 910.30	229.90
Fujian	299	5.20	75.2	465.630	3 714.93	234.20
Jiangxi	403	7.74	29.8	447.670	2 963.97	92.80
Shandong	1 284	17.87	117.3	1 369.300	3 287.19	365.39
Henan	1 320	12.22	95.2	1 454.130	2 779.77	296.50
Hubei	928	19.92	61.5	939.820	2 930.23	191.60
Hunan	785	15.07	47.2	957.470	2 905.99	147.00
Guangdong	722	3.71	86	890.330	3 508.42	267.90
Guangxi	857	27.46	48.8	815.810	2 591.84	152.00
Hainan	173	0.96	13.5	234.500	2 842.21	42.10
Chongqing	389	3.03	21.3	398.850	2 871.35	66.30
Sichuan	1 602	24.02	46.9	1 309.880	2 776.05	146.10
Guizhou	693	6.55	10.4	632.620	2 037.88	32.40
Yunnan	1 225	26.61	28.6	865.610	2 251.97	89.10
Shaanxi	649	21.55	91.5	629.760	2 334.78	285.00
Gansu	614	7.62	36	367.020	1 808.62	112.10
Qinghai	72	0.58	6.5	80.380	2 149.24	20.20
Ningxia	94	4.07	20.7	115.830	2 442.72	64.50
Xinjiang	481	13.32	87.2	752.180	2 460.56	271.60

DMU – Decision-making unit
Source: Compiled by the authors based on the China Statistical Yearbook 2023

leading to inaccuracies in efficiency assessments. When undesirable outputs are ignored, the objective function of Model (6) becomes Equation (7):

We also calculated the efficiency of the 30 DMUs while ignoring undesirable outputs. Table 5 summarises the results.

In terms of overall efficiency, Shanxi, Jilin, Anhui, Guangxi, Shaanxi, and Gansu were inefficient, whereas the remaining DMUs were efficient. Among these inefficient DMUs, Gansu's efficiency was only 0.7975, which was the poorest performance. From the perspective of the agricultural subsystems, Shanxi, Anhui, and Gansu were inefficient. Gansu exhibited the poorest performance, with an efficiency of 0.7697. The other DMUs were found to be efficient. For the pastoral subsystems, Shanxi, Hubei, Sichuan, and Guizhou

$$E = \min \ 1 - \sum_{p}^{P} \frac{w_p}{I_p + S_p + I_g + S_g} \left(\sum_{i=1}^{I_p} \frac{s_{pi}^-}{B_{pi}^-} + \sum_{r=1}^{S_p} \frac{s_{pr}^+}{B_{pr}^+} + \sum_{i_g=1}^{I_g} \frac{s_{pi_g}^-}{B_{pi_g}^-} + \sum_{r_g=1}^{S_g} \frac{s_{pr_g}^+}{B_{pr_g}^+} \right) \tag{7}$$

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Table 4. Results

DMU	Overall efficiency	Efficiency of the agricultural subsystem	Efficiency of the pastoral subsystem
Beijing	1	1	1
Tianjin	1	1	1
Hebei	1	1	1
Shanxi	0.8943	0.8238	1
Inner Mongolia	1	1	1
Liaoning	1	1	1
Jilin	0.9625	1	0.9065
Heilongjiang	1	1	1
Shanghai	1	1	1
Jiangsu	1	1	1
Zhejiang	1	1	1
Anhui	0.9025	0.8375	1
Fujian	1	1	1
Jiangxi	1	1	1
Shandong	1	1	1
Henan	1	1	1
Hubei	1	1	1
Hunan	1	1	1
Guangdong	1	1	1
Guangxi	0.9612	1	0.9031
Hainan	1	1	1
Chongqing	1	1	1
Sichuan	1	1	1
Guizhou	1	1	1
Yunnan	1	1	1
Shaanxi	0.9379	1	0.8447
Gansu	0.8032	0.7695	0.8537
Qinghai	1	1	1
Ningxia	1	1	1
Xinjiang	1	1	1

DMU – decision-making unit
Source: Author's own calculation

Table 5. Results under the condition of ignoring undesirable outputs

DMU	Overall efficiency	Efficiency of the agricultural subsystem	Efficiency of the pastoral subsystem
Beijing	1	1	1
Tianjin	1	1	1
Hebei	1	1	1
Shanxi	0.8885	0.8142	0.8968
Inner Mongolia	1	1	1
Liaoning	1	1	1
Jilin	0.9587	1	1
Heilongjiang	1	1	1
Shanghai	1	1	1
Jiangsu	1	1	1
Zhejiang	1	1	1
Anhui	0.8958	0.8263	1
Fujian	1	1	1
Jiangxi	1	1	1
Shandong	1	1	1
Henan	1	1	1
Hubei	1	1	0.8934
Hunan	1	1	1
Guangdong	1	1	1
Guangxi	0.9573	1	1
Hainan	1	1	1
Chongqing	1	1	1
Sichuan	1	1	0.8292
Guizhou	1	1	0.8390
Yunnan	1	1	1
Shaanxi	0.9317	1	1
Gansu	0.7975	0.7697	1
Qinghai	1	1	1
Ningxia	1	1	1
Xinjiang	1	1	1

DMU – decision-making unit
Source: Author's own calculation

were inefficient, with efficiencies below 1. Sichuan exhibits the poorest performance.

For a more intuitive comparison of the efficiencies under different conditions, Figure 3 summarises the comparative results.

Figure 3A showed the comparison results for overall efficiency. It can be observed that Shanxi, Jilin, Anhui, Guangxi, Shaanxi, and Gansu have higher efficiency under the slacks-based measure condition compared to that under the condition of ignoring undesirable outputs. The efficiency of the other DMUs was one under both conditions, indicating that there was no gap between them.

Figure 3A showed the results for the efficiency of the agricultural subsystems. Shanxi and Anhui show higher efficiency under the slacks-based measure condition than that under the condition of ignoring undesirable outputs. However, Gansu had lower efficiency under the slack-based measure condition than under the condition of ignoring undesirable outputs. The remaining DMUs exhibit the same efficiency under both conditions.

Figure 3C summarises the comparative results for the efficiency of the pastoral subsystems. Shanxi, Hubei, Sichuan, and Guizhou exhibited higher efficiency under the slacks-based measure condition than when undesirable outputs were ignored. Jilin, Guangxi, Shaanxi, and Gansu have lower efficiencies under slack-based measure conditions than when undesirable

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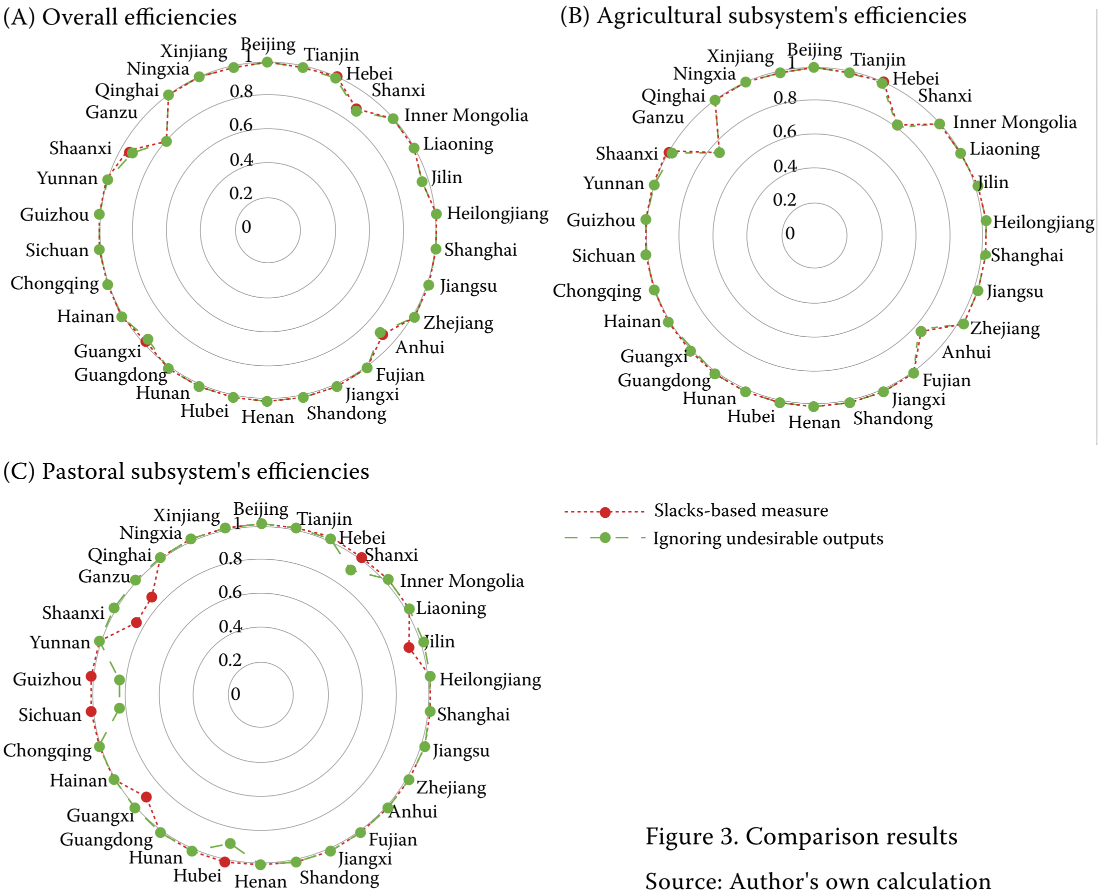

Figure 3. Comparison results

Source: Author's own calculation

outputs were ignored. The efficiency values of the other DMUs were equal under both conditions.

It is unscientific to ignore undesirable outputs. For example, from the overall efficiency data, Shanxi's efficiency under the slack-based measure condition was higher than when undesirable outputs were ignored. The value of CO_2 for Shanxi was 78.5, ranking lowest among the 30 DMUs. The efficiency of Shanxi is expected to be higher because of its lower CO_2 emissions. Therefore, it is unscientific to state that efficiency under the condition of ignoring undesirable outputs is lower than that under the slack-based measure condition for Shanxi. Thus, a slack-based measure is appropriate for addressing CO_2 emissions. Ignoring undesirable outputs may misestimate efficiency.

CONCLUSION

Assessing and optimising the efficiency of agricultural and pastoral systems is crucial for the long-term development of a country. The presence of shared factors and undesirable outputs increases the complexity of evaluating the efficiencies of these systems. To address this issue, we proposed two BAM models that consider shared factors and undesirable outputs to evaluate the divisional efficiency of agricultural and pastoral subsystems, respectively. Additionally, a network BAM model in the presence of shared factors and undesirable outputs was developed to assess the overall efficiency.

New models were applied to evaluate the efficiency of agricultural and pastoral systems across 30 Chinese provinces and cities. The evaluation results were analysed. We also investigated the efficiency while ignoring undesirable outputs. By comparing the results under slack-based measurement conditions, we found that ignoring undesirable outputs may lead to an inaccurate estimation of efficiency.

In our study, the agricultural and pastoral subsystems were treated as black boxes. The internal structures of these subsystems have not been investigated. Future research can explore the internal connections between the agricultural and pastoral subsystems. Based on the proposed model, a model for evaluating the efficiency of multistage agricultural and pastoral systems can be developed. In addition, other specific

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factors, such as undesirable inputs and dual-role factors, can be integrated into the new model.

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