Technical Efficiency, Ecological Efficiency and Grassland Ecological Performance of Grazing in China

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Abstract:

Incorporating the ecological variable of grassland Net Primary Productivity (NPP) into the production function - to be representative of grassland quality - is a new step toward the ecological efficiency analysis under the field of productivity and efficiency analysis. We measure the technical efficiency, ecological performance indicator and ecological efficiency of grazing using a multi-outputs and multi-inputs stochastic input-oriented distance function. The average technical efficiency is estimated to be 0.90 when taking grassland NPP into account, implying that cost of grazing inputs can be decreased by 10% without any deduction of outputs. The ecological efficiency is estimated to be 0.83 and the average ecological performance indicator is 0.17.

Key words: Technical efficiency; Ecological efficiency; Ecological performance indicator; Net primary productivity (NPP); input distance function.

1. Introduction

The concerns about environmental problems pushed by local economic development in developing countries received a lot of attention in recent years; as one of the main land use types on earth is grassland, the relationship between environmental problems caught by inappropriate grassland use and local economic development became a popular topic. Although grassland is essential for livestock grazing and grassland ecosystem service supply, three quarters of the world's grazing lands are so degraded that they have lost more than 25% of their capacity to support animals (White, *et al.*, 2000; UNEP, 2005). The Sanjiangyuan grassland area is one of the biggest grassland areas in China. Located on the Qinghai-Tibetan Plateau, Sanjiangyuan is heavily affected by advancing grassland degradation over wide areas as a result of overgrazing, cropland misuse and unregulated collection of fuel and medical plants (Akiyama, *et al.*, 2006; Zhou, *et al.*, 2006; Zhang, 2008). Livestock grazing is the most widespread land management practice on the Qinghai-Tibetan Plateau and long-term overgrazing is criticized to be one of the principal factors causing grassland degradation. Therefore strong relationships between grassland degradation and grassland grazing have made us interested in researching the technical efficiency and ecological efficiency of grassland as well as the ecological performance indicator of grassland quality for grazing in this paper.

Eco-efficiency and environmental efficiency became heated topics under the field of productivity and efficiency analysis in economics literature, which are developed to express how the performance of ecological factors and environmental factors meet human demand (OECD, 1998; Huppes and Ishikawa, 2005). The formal definition of eco-efficiency was probably generally defined by the World Business Council for Sustainable Development (WBCSD) at the beginning of the 1990s (WBCSD, 1992). They described eco-efficiency as a ratio of reduced environmental impact and the increased value of production. Under the subject of ecological efficiency and environmental analysis over the last30 years, there have been three main frameworks. Firstly, ecological efficiency is usually measured by comparing environmental performances. Different empirical environmental methodologies have been proposed for the measurement of the environmental performance of production units (Yaisawarng and Klein, 1994; Fare, *et al.*, 1996; Tyteca, 1996; Picazo-Tadeo, *et al.*, 2014). Secondly, environmentally detrimental inputs and pollution are treated as inputs in the production function (Pittman, 1981; Reinhard, *et al.*, 1999; Reinhard, *et al.*, 2000; Reinhard, *et al.*, 2002). Thirdly, environmental effects are treated as undesirable outputs, "bad outputs", in the production function (Färe, *et al.*, 1986; Färe, *et al.*, 1989; Färe, *et al.*, 2005; Van Ha, *et al.*, 2008; Cuesta, *et al.*, 2009; Picazo-Tadeo, *et al.*, 2014). Both of the nonparametric (e.g. data envelope analysis, non-parametric hyperbolic distance function) and parametric approaches (e.g. distance function, directional distance function) have been used frequently in the measurement of ecological efficiency and environmental efficiency.

Typically land is one of the necessary inputs in agricultural crop farming or livestock farming. There are lots of research publications under the field of productivity and efficiency analysis taking into account the land area as one of the inputs, either for crop farming (Abdulai and Eberlin, 2001; Pascual, 2005; Brümmer, *et al.*, 2006; Galdeano-Gómez and Céspedes-Lorente, 2008; Chen, *et al.*, 2009; Zhang, *et al.*, 2011; Asante, *et al.*, 2014) or for livestock grazing or dairy farming (Morrison Paul, *et al.*, 2000; Brümmer, *et al.*, 2002; Lansink, *et al.*, 2002; Morrison Paul and Nehring, 2005; Otieno, *et al.*, 2014; Sauer and Latacz-Lohmann, 2014). However, few papers consider the heterogeneous land quality, such as soil nutrients, soil types or soil conservation (Reinhard, *et al.*, 2002; Latruffe, *et al.*, 2004; Bozoglu and Ceyhan, 2007; Hoang and Alauddin, 2012; Marchand, 2012; Rao, *et al.*, 2012). To the best of our knowledge, almost no paper focuses on the ecological efficiency of grassland grazing, and takes the grassland quality into account in grazing on the Qinghai-Tibetan Plateau in China. As the large scale characteristic of grassland on the Qinghai-Tibetan Plateau, the average pasture area is about 800 Mu[1] for each grazing family; grassland quality is heterogeneous in terms of grass diversity, soil nutrients and so on (Li, *et al.*, 2013). Unlike livestock dairy farming, where resource and human management plays an important role in production potential, livestock grazing relied heavily on grassland quality. In order to calculate the grassland ecological performance and ecological efficiency, we incorporate the ecological variable, grassland Net Primary Productivity (NPP), to be representative of grassland quality in this paper.

We extend the contribution of Reinhard *et al.* (1999, 2002) on environmental efficiency by incorporating the grassland NPP as representative of grassland quality and define the ecological performance indicator by comparing the technical efficiencies from the unlimited model and the limited model. The stochastic input oriented distance function with MLE estimation procedure is developed by using household level data on livestock grazing. We would like to stress a deeper understanding of the significance of grassland quality and to support the policy maker to modify or make suitable new policies to help sustainable development of the regional ecological environment.

The structure of the paper is as follows. Section 2 presents the theoretical framework, methodology and empirical model specification. Section 3 contains data and statistical descriptions. The empirical model analysis results are presented in section 4, followed by section 5 which concludes with our discussion.

2. Theoretical framework and methodology

In order to estimate the technical efficiency, ecological efficiency and ecological performance indicator of an ecological variable (Net Primary Productivity, NPP), a multi-input multi-output livestock grazing function incorporating the ecological variable as one of the inputs is developed. We estimate the stochastic frontier production function and technical inefficiency model first, derived from which we get the ecological performance indicator and ecological efficiency. As livestock grazing on the Tibetan Plateau still adopts a traditional nomadic pastoral system (Davies and Hatfield, 2007; Harris, 2010), this might be advantageous for the distance function, not considering the price of inputs and outputs at this moment in time. Given the properties of output distance function and input distance function, we use an input-oriented stochastic distance function to address our research questions in this

[1] 1 Mu = 1/15 Hectare

paper, as traditional livestock grazing on the Tibetan Plateau heavily relies on the grassland area and grass quality (represented by NPP) and the input-oriented stochastic distance function sheds more light on input, as NPP. We adopt the stochastic distance function approach instead of a deterministic approach because of the ability to separate the random noise from the technical inefficiency term.

2.1. Conceptual framework

We followed the distance function methodology developed by Shephard (Shephard, 1970), which treats the outputs as given and adjusts the input vectors as long as the input-output vectors are still technologically feasible in the input distance function. Defining yak herding households using input sets, $L(y)$, which represent the set of all input vectors, $x \in \Re^{K+}$, can be produced by output vector sets $y \in \Re^{M+}$, which can be written with the input possibility set $L(y) = \{x: x \text{ can produce } y\}$, which is assumed to satisfy the set of axioms depicted in Färe (1996). The input distance is then defined in the input set, $L(y)$, as$D_I\ (x, y) = \sup\{\rho: (y/\rho) \in L(y)\}$.

In order to estimate the distance function in a parametric setting, a translog functional form is used by normalizing the function by one of the , specified as

$$\ln(D_{Ii}(x,y)/X_{Ki}) = \alpha_0 + \sum_{k=1}^{K-1} \alpha_k lnX^*_{ki} + \frac{1}{2}\sum_{k=1}^{K-1}\sum_{l=1}^{L-1} \alpha_{kl}\, lnX^*_{ki} lnX^*_{li} + \sum_{m=1}^{M} \beta_m lnY_{mi} + \frac{1}{2}\sum_{m=1}^{2}\sum_{n=1}^{2} \beta_{mn}\, lnY_{mi} lnY_{ni} + \sum_{k=1}^{K-1}\sum_{m=1}^{M} \delta_{km} lnX^*_{ki} lnY_{mi}\,. \quad i = 1,2,\cdots,N. \tag{1}$$

where $X^*_{ki} = x_{ki}/x_{Ki}$. This equation may be more concisely expressed as:

$$\ln(D_{Ii}(x,y)/X_{Ki}) = TL(x_{ki}/x_{Ki}, y_{mi}, \alpha, \beta, \delta), \tag{2}$$

Hence we set $u = \ln(D_{Ii}(x,y))$. According to Aigner, Lovell and Schmidt (1977), we get the stochastic frontier model by adding a term v_i to capture noise. Thus the stochastic output distance function is shown to be: $-\ln(X_{Ki}) = TL(x_{ki}/x_{Ki}, y_{mi}, \alpha, \beta, \delta) + v_i - u_i$,where v_i ~ i.i.d. $N(0, \sigma_v^2)$ and u_i ~$N(\mu_i, \sigma_u^2)^+$, $i = 1,2,\cdots,N$.

The mean μ_i is defined as the technical inefficiency model, $\mu_i = \tau_0 + Z_i * \tau_i$, (3)

where Z_i is a vector of explanatory variables associated with the technical inefficiency effects, τ_0 is the constant item of the technical inefficiency model, and τ_i is a vector of unknown parameter to be estimated (Battese and Coelli, 1988, 1995; Battese, *et al.*, 1996). Maximum Likelihood Estimation (MLE) could be used to estimate the parameters (Aigner, *et al.*, 1977).

Technical efficiency (TE) is defined as the ratio of the observed output to the corresponding potential output given the production frontier, specified as $Y_i = f(X_i, \beta).\exp(v_i - u_i)$. Therefore the technical efficiency is written as in equation (4).

$$TE_i = \frac{f(X_i,\beta).\exp(v_i - u_i)}{f(X_i,\beta).\exp(v_i)} = \exp(-u_i) = \frac{1}{\ln(D_{Ii}(x,y))}, \qquad i = 1,2,\cdots,N. \tag{4}$$

The ecological performance indicator (EPI) is defined as the ratio of the distance function values obtained from the production function incorporating ecological input to that without ecological input (Fare, *et al.*, 1993; Fare, *et al.*, 1996; Tyteca, 1997; Hailu and Veeman, 2000). The EPI is then written as follows:

$$EPI_i = \frac{D_{Ii}(x\ eco,y) - D_{Ii}(x,y)}{D_{Ii}(x,y)} = \frac{TE_i(x\ eco,y) - TE_i(x,y)}{TE_i(x,y)}, \quad (5)$$

$EPI_i > 0$ means that incorporating with NPP would decrease the distance from the frontier and increase the technical efficiency, $EPI_i < 0$ otherwise.

Ecological efficiency (EE) is defined as the ratio of minimum feasible ecological input use to observed ecological input use, conditional on observed levels of the other inputs and outputs (Reinhard, *et al.*, 1999).

$$EE_i = \frac{min.\ feasible\ ecological\ input}{observed\ ecological\ input}, \quad (6)$$

2.2 Empirical model specification and estimation measurement

Empirically, for livestock grazing on the Qinghai-Tibetan Plateau we set the unlimited functional form for the parametric distance function of livestock grazing as equation (7).

$$\begin{aligned}
&-\ln(X_{5i}) \\
&= \alpha_0 \\
&+ \sum_{k=1}^{3} \alpha_k lnX^*_{ki} + \frac{1}{2}\sum_{k=1}^{3}\sum_{l=1}^{3} \alpha_{kl}\, lnX^*_{ki} lnX^*_{li} + \sum_{m=1}^{2} \beta_m lnY_{mi} + \frac{1}{2}\sum_{m=1}^{2}\sum_{n=1}^{2} \beta_{mn}\, lnY_{mi} lnY_{ni} \\
&+ \sum_{k=1}^{3}\sum_{m=1}^{2} \delta_{km} lnX^*_{ki} lnY_{mi} + \sum_{k=1}^{3} \alpha'_k X'_{ki} \\
&+ \boxed{\alpha_4 lnNPP^*_i + \frac{1}{2}\alpha_{44}(lnNPP^*_i)^2 + \sum_{k=1}^{3} \alpha_{k4} lnX^*_{ki} lnNPP^*_i + \sum_{m=1}^{2} \delta_{4m} lnNPP^*_i lnY_{mi}} + v_i \\
&- u_i, \qquad i = 1,2,\cdots,N. \qquad (7)
\end{aligned}$$

where $X^*_{ki} = X_{ki}/X_{4i}$, $NPP^*_i = NPP_i/X_{4i}$. Y_i denotes the vector of outputs: y_1 describes the output of livestock grazing, denoted by the yak meat produced in the year; y_2 denotes the revenue of the other outputs, including the revenue of Tibetan sheep, milk, yak hide, Tibetan sheep wool and so on. X_i is a vector of inputs with x_1 = grassland area, x_2 = labor, x_3=household capital, x_4= Net Primary Productivity (NPP) in 2011, and x_5 = initial yak at the beginning of the year. X'_{ki} is a vector of controllable inputs including household size, temperature (January 2010) and precipitation (July 2010). In order to get the technical efficiency from the production function without incorporating the ecological input NPP, we remove all terms with NPP (the items inside the rectangle) from equation (8) and get the limited model.

We get technical efficiency (TE_i) from the MLE estimation of equation (7) where the production function incorporates the NPP, as well as technical efficiency (TE^l_i) from the estimation of the production function not incorporating NPP. We then define the ecological performance indicator as shown in equation (8):

$$\text{Ecological Performance Indicator } (\text{EPI}_i) = \frac{TE_i - TE^l_i}{TE^l_i} \quad (8)$$

For the estimation of ecological efficiency, we assume that the producer would be the most ecological efficiently when they use the minimum optimal amount of NPP. The logarithm input oriented production function of an ecological efficiency producer is then obtained by replacing observed NPP and u_i with $\overline{NPP_i}$ and $\overline{u_i}$ respectively. The ecological efficiently livestock grazing function is then written as shown in equation (9),

$$-\ln(X_{5i}) = \alpha_0 + \sum_{k=1}^{3}\alpha_k lnX_{ki}^* + \frac{1}{2}\sum_{k=1}^{3}\sum_{l=1}^{3}\alpha_{kl}\, lnX_{ki}^* lnX_{li}^* + \sum_{m=1}^{2}\beta_m lnY_{mi} + \frac{1}{2}\sum_{m=1}^{2}\sum_{n=1}^{2}\beta_{mn}\, lnY_{mi} lnY_{ni} + \sum_{k=1}^{3}\sum_{m=1}^{2}\delta_{km} lnX_{ki}^* lnY_{mi} + \alpha_4 ln\overline{NPP}_i^* + \frac{1}{2}\alpha_{44}(ln\overline{NPP}_i^*)^2 + \sum_{k=1}^{3}\alpha_{k4} lnX_{ki}^* ln\overline{NPP}_i^* + \sum_{m=1}^{2}\delta_{4m} ln\overline{NPP}_i^* lnY_{mi} + \sum_{k=1}^{3}\alpha_k' X_{ki}' + v_i - \overline{u_i} \quad (9)$$

where $\overline{NPP_i}$ means the optimal ecological input *NPP (x4)* should be used for full ecological efficiency. Let equation (7) be equal to equation (9), allowing us to isolate the logarithm ecological efficiency (denoted by equation (10)) by using equation (11).

$$lnEE_i = ln\frac{\overline{NPP_i}}{NPP_i} = ln\overline{NPP}_i - lnNPP_i \quad (10)$$

$$\frac{1}{2}\alpha_{44}\left[\left(ln\overline{NPP}_i\right)^2 - (lnNPP_i)^2\right] + \left(\alpha_4 + \sum_{k=1}^{3}\alpha_{k4}\, lnx_{ki}^* + \sum_{m=1}^{2}\delta_{4m}\, lny_{mi}\right)\left(ln\overline{NPP}_i - lnNPP_i\right) - \overline{u_i} + u_i = 0 \quad (11)$$

Let a $=\frac{1}{2}\beta_{55}$, b=$\alpha_4 + \sum_{k=1}^{3}\alpha_{k4}\, lnx_{ki}^* + \sum_{m=1}^{2}\delta_{4m}\, lny_{mi}$, c=$-\overline{u_i} + u_i$, and let $\overline{u_i}$ = 0 by assuming the yak producer household would operate technically efficiently[2] if they operate ecologically efficiently, therefore we can get the ecological efficiency from the following equation[3].

$$lnEE_i = ln\frac{\overline{NPP_i}}{NPP_i} = ln\overline{NPP}_i - lnNPP_i = \frac{-b\pm\sqrt{b^2-4ac}}{2a} \quad (12)$$

Finally, the ecological efficiency *EE* is calculated as $EE_i = e^{lnEE_i}$.

3. Data and descriptive statistics

We illustrate the translog input distance function by calculating the technical efficiency, ecological efficiency and ecological performance indicator based on a set of 197 yak herder households. The social-economic data was drawn from field survey questionnaires in the Sanjiangyuan region of Qinghai province on the Qinghai-Tibetan Plateau, conducted by the Center for Chinese Agricultural Policy at the Chinese Academy of Sciences in August and October, 2012. The Net Primary Productivity data (NPP) is computed by the Institute of Geographic Sciences and Natural Resources Research at the Chinese Academy of Sciences by using 1km pixel data for the global vegetated land surface downloaded from the website of National Aeronautics and Space Administration in the USA.

We statistically summarized the outputs, inputs and farm-specific variables before estimating the stochastic frontier function and technical inefficiency model (Table 1). Classic

2 Actually, the assumption of a producer operating ecologically efficiently necessarily being technically efficient may not exist. We calculated the EE by assuming the $\overline{u_i}$ = 0.90 or 0.80, instead of $\overline{u_i} = 0$, the results don't change the rankings of EE. Finally we adopted this assumption in order to be methodologically consistent with previous research (Reinhard, Lovell and Thijssen, 1999).

3 As for equation (15), we could get two EE_i from $lnEE_i = \frac{-b+\sqrt{b^2-4ac}}{2a}$ and $lnEE_i = \frac{-b-\sqrt{b^2-4ac}}{2a}$ respectively. We take the first one for analysis in this paper.

inputs are aggregated into four categories: grassland area (*x1*), labor (x_2), capital (x_3), the ecological variable Net Primary Productivity (NPP or x_4) and initial yak (x_5). Meanwhile, outputs are aggregated into two categories: yak meat (y_1) and the revenue of the other outputs (y_2). The ecological variable grassland Net Primary Productivity (NPP) - input (x_4) in this paper, is representative of grassland quality in general. NPP refers to the net production of organic matter assimilated by autotrophic organisms measured in a given unit of area over a specified time, which is equal to the total amount of organic carbon assimilated by grassland vegetation minus organic carbon lost by autotrophic photorespiration (Roxburgh, *et al.*, 2005; Zhao and Running, 2010). Computationally, after matching the rough boundary of summer pasture and winter pasture to the 1km NPP raster data file and getting samples of NPP for each pasture according to the pasture area, we summarize the NPP of pastures for each household. The NPP imported in the stochastic distance function and technical inefficiency model in this paper is the average annual grassland NPP of summer pasture and winter pasture in 2011.

Table 1. Summary of variables in the frontier and inefficiency model

Variable	Unit	Symbol	Mean	Std. Dev.
Yak output	kg	y_1	5.69E+03	6.93E+03
Others revenue	yuan	y_2	9.43E+03	2.23E+04
Grassland area	mu	x_1	9.02E+02	1.39E+03
Labor	herd	x_2	2.30E+00	1.27E+00
Capital	yuan	x_3	1.58E+05	3.08E+05
Net Primary Productivity 2010	gc/m2	x_4 *or NPP*	2.69E+03	5.48E+02
Initial yak at the beginning of 2011	kg	x_5	7.91E+03	1.16E+04
Household size	herd	*HHsize*	4.71E+00	1.66E+00
Temperature January 2010	0.01℃	*Tprt*	-4.97E+00	6.98E+01
Precipitation July 2010	0.01mm	*Prct*	9.51E+03	4.85E+03

Operational and farm-specific variables are household size, the average temperature in January 2010 and precipitation in July 2010. Household size *(HHsize)* is the population of one family. We collected the average temperature of January 2010 (*Tprt*) and the precipitation of July 2010 (*Prct*) from the China Meteorological Administration and Qinghai Province meteorological stations' records in the Sanjiangyuan region. According to the location and area of pastures, we interpolated the precipitation data and temperature data from meteorological stations in each county for this paper. For a better interpretation of the estimation results, farm-specific variables are normalized by subtracting the mean (Zhang et al., 2011).

4. Results

Prior to presenting estimates, we tested the hypothesis that the Cobb-Douglas function is a statistically suitable representation of the data, which is strongly rejected by the likelihood ratio test. We used the Maximum Likelihood Estimation method to estimate the input oriented distance function and technical inefficiency model, then calculated the ecological performance indicator of grassland NPP and ecological efficiency.

4.1 Stochastic distance function estimates

Maximum likelihood estimates of the stochastic distance function are presented in table 2, where columns (1) and (2) represent the results of the unlimited model incorporating grassland NPP into the production function and the technical inefficiency model. Columns (3) and (4) show the results of the limited model where grassland NPP is not incorporated into the production function. The overall model's qualities seem satisfactory according to the likelihood ratio tests and t-ratios. *VAR (u)/VAR(total)* are estimated to be 0.996 and 0.751 in an unlimited model and limited model, respectively, meaning that the variances in the herder household specific error terms are greater than the variances in the stochastic error terms. These results reveal that the one-sided inefficiency random components dominate the measurement errors and other random disturbances. By the likelihood ratio test, we can see that the unlimited model which incorporates grassland NPP is better than the limited model (Table4).

Table 2. Estimates of stochastic distance function

Variable	Unlimited model (1) Coef.	(2) S.E.	Limited model (3) Coef.	(4) S.E.
Stochastic frontier estimates of distance function				
Dependent Variable: *ln(x4)*				
Constant	0.071***	0.016	0.069	0.058
$ln(y_1)$	0.017	0.018	0.244***	0.065
$ln(y_2)$	0.005	0.006	0.036**	0.016
$ln(x_1)$	-0.086***	0.014	-0.185***	0.039
$ln(x_2)$	-0.091***	0.021	-0.533***	0.068
$ln(x_3)$	-0.048***	0.013	-0.06	0.051
$ln(x_4)$	-0.792***	0.026		
$0.5\ ln(y_1)$^2	0.022	0.020	0.137**	0.062
$0.5\ ln(y_2)$^2	0.001	0.001	0.006*	0.003
$0.5\ ln(x_1)$^2	-0.040***	0.009	-0.045	0.034
$0.5\ ln(x_2)$^2	-0.144***	0.054	-0.075*	0.042
$0.5\ ln(x_3)$^2	-0.013	0.010	0.008	0.029
$0.5\ ln(x_4)$^2	-0.162***	0.062		
$ln(y_1)ln(y_2)$	-0.007	0.005	-0.004	0.007
$ln(y_1)ln(x_1)$	0.016	0.022	0.113**	0.049
$ln(y_1)ln(x_2)$	0.043*	0.023	0.019	0.03
$ln(y_1)ln(x_3)$	0.012	0.016	0.01	0.042
$ln(y_1)ln(x_4)$	-0.019	0.031		
$ln(y_2)ln(x_1)$	0.002	0.003	-0.005	0.007
$ln(y_2)ln(x_2)$	0.004	0.004	0.006	0.005
$ln(y_2)ln(x_3)$	-0.004*	0.002	-0.002	0.007
$ln(y_2)ln(x_4)$	-0.01	0.006		
$ln(x_1)ln(x_2)$	0.018	0.016	0.119***	0.028
$ln(x_1)ln(x_3)$	0.017*	0.010	-0.011	0.036
$ln(x_1)ln(x_4)$	0.021	0.020		
$ln(x_2)ln(x_3)$	0.009	0.010	0.03	0.04
$ln(x_2)ln(x_4)$	0.164***	0.050		
$ln(x_3)ln(x_4)$	-0.001	0.015		
Hhsize	0.033***	0.008	0.058***	0.019
Tprt	0.059***	0.005	0.0003	0.010
Prct	0.001***	0.000	0.001	0.000
Ln(sigma_v)	-2.955***	0.090	-1.812***	0.079

Table 3. Estimates of technical inefficiency model.

Variable	Unlimited model (5) Coef.	(6) S.E.	Limited model (7) Coef.	(8) Robust S.E.
Estimates of technical inefficiency model				
Dependent Variable: *technical inefficiency*				
Constant	-3.117***	0.136	-2.708***	0.222
$ln(x_1)$	-0.549***	0.116	-0.557***	0.167
$ln(x_2)$	-0.594***	0.172	-2.081***	0.189
$ln(x_3)$	-0.208*	0.115	-0.121	0.129
$ln(x_4)$	-4.915***	0.517		
$ln(x_5)$	0.045	0.113	-0.012	0.094
Hhsize	0.293***	0.070	0.196**	0.086
Tprt	0.826***	0.063	1.607	1.577
Prct	0.005*	0.003	0.001	0.002

Notes: Statistically significant at levels of *0.10, **0.05, and ***0.01.

Table 4. Model identification for table2 and table3

Item	Unlimited model	Limited model
log-likelihood value	222.9	29.4
parameters' number	41	33
AIC	-1.847	0.369
gamma:	0.998	0.892
VAR(u)/VAR(total)	0.996	0.751

Table 5. Summary of TE, EPI and EE

Variable	Mean	Std. Dev.	Min	Max
TE of unlimited model	0.900	0.113	0.376	0.999
TE of limited model	0.816	0.186	0.274	0.999
EPI	0.174	0.384	-0.496	1.786
EE	0.834	0.007	0.817	0.850

Table 6. Summary of TE and EE group on EPI

Efficiency	EPI > 0 Mean	S.D.	EPI < 0 Mean	S.D.
TE of unlimited model	0.933	0.081	0.839	0.136
Ecological efficiency (EE)	0.832	0.006	0.840	0.005
Obs. number (%)	128 (65%)		69 (35%)	

Columns (1) and (2) of table 2 present the stochastic frontier analysis results of the unlimited model. All of the first order coefficients of the inputs and outputs have the expected signs indicating positive partial production elasticity at the sample mean, with coefficients of all inputs significantly different from zero at the 1% level. In terms of the magnitude of elasticity at the sample mean, the grassland area *(x_1)*, the labor *(x_2)* and capital *(x_3)* are all important for livestock grazing, especially when the magnitude of the coefficient of grassland NPP *(x_4)* is larger. The elasticity of the input oriented distance function with respect to input quantity reflects the relative importance of input to production potential. The elasticity with respect to grassland area is estimated with a value of 0.086, implying that the cost of grassland area represents 8.6% of the total cost at the sample mean. The elasticity with respect to labor and capital is estimated to be 0.091 and 0.048, respectively, both of which are significantly different from 0 at 0.01 statistically level. The highest elasticity to production potential is from grassland NPP, which is estimated to be 0.792; the cost share of grassland NPP to total cost is 79.2%, which is greater than other inputs. It is surprising to see that the input elasticity of grassland NPP is substantially important for yak grazing production, which meets our expectation well. Most of the second order coefficients of the inputs have the correct signs, as expected.

With reference to the unlimited model, we estimated the stochastic input distance function not incorporating grassland NPP, which is presented in columns (3) and (4) of table 2. It shows that the elasticity of two outputs are significantly different from zero, implying that increasing the production of either of these outputs will increase distance substantially. The estimate also shows that the elasticity of output1 is 0.244, whereas the estimate for output2 is only 0.036. This means that a 1% increase in output 1 will increase distance by 24.4%, while the corresponding figure for output2 is only 3.6%. Elasticity of grassland area and labor are still statistically significant in the limited model whereas the elasticity magnitude of labor is greater than that in the unlimited model. Comparing stochastic estimates of both the unlimited and limited models, we can see the important role of grassland NPP in both the stochastic distance function and the technical inefficiency model. The implication is that the ecological input grassland NPP plays a significant role in the yak grazing production and the contribution of grassland NPP is significantly higher than other inputs.

Household specific variables such as household size *(Hhsize)*, precipitation in July *(Prct)* and temperature in January *(Tprt)* play essential roles in production functions as well. The coefficient of household size is estimated to be robust in both the unlimited model and the limited model, with values of 0.033 and 0.058 respectively, meaning that the bigger the household, the lower the production potential. Weather variables such as temperature and precipitation are estimated to only be significantly in the unlimited model. After normalizing these inputs by subtracting the sample mean from them, it is easier to interpret the coefficients directly. Estimates of weather variables indicate that higher temperatures in June and more precipitation in July would result in a decrease of the production potential.

4.2 Technical inefficiency model estimates and technical efficiency

The determinants for the variation of a yak herder household's technical inefficiency are estimated in the technical inefficiency model (Table 3). Because technical inefficiency is the dependent variable in the technical inefficiency model, a negative parameter coefficient for the variables indicates a negative effect on technical inefficiency and conversely a positive effect on technical efficiency.

Grassland area *(x_1)* and labor *(x_2)* have statistically significant effects on the technical inefficiency in both the unlimited and limited models. All of the coefficients are statistically significant at the 1% level, meaning that grassland area and labor are negative on technical inefficiency, and therefore positive to technical efficiency. It is not strange to see that the estimate of grassland NPP *(x_4)* is statistically significant to technical inefficiency; it is reasonable to think that better grassland quality will result in higher technical efficiency. Household size *(Hhsize)* is estimated to be statistically significant in relation to technical inefficiency. The coefficient of household size (*HHsize*) is estimated to be positively statistically significant at least a level of 5% in both the unlimited and limited models, indicating that the bigger the household is, the less technically efficient their production will be. As to the estimates of the precipitation in July *(Prct)* and temperature in January *(Tprt)*, both of the two weather variables are estimated to be positive in relation to technical inefficiency, which means that the higher the temperature is in July, the more the precipitation in January would enhance the technical inefficiency.

After estimating the stochastic distance function and technical inefficiency model, we calculate each household's technical efficiency in both the unlimited and limited models. The average estimated technical efficiency for yak herder households in the unlimited model is 0.90, which indicates that on average, yak rearing households can reduce about 10% of cost of inputs given the present status of technology and the output level. The average technical efficiency for yak herder households in the limited model is about 0.82, which proves that the grassland NPP is important for technical efficiency and the incorporation of grassland NPP can enhance the technical efficiency (Table5). From the range distribution of technical efficiencies from the unlimited and limited models (Figure1), we can see that about 49% of households have a technical efficiency score equal to or more than 0.95 in the unlimited model, with 34% in limited model. Whereas 22% of households have efficiency scores greater than or equal to 0.90 and less than 0.95 in the unlimited model, with 16% in limited model. 7% of households have efficiency scores more than or equal to 0.85 and less than 0.90 in the unlimited model, with 10% households in the limited model. 7% of the households have efficiency scores more than or equal to 0.80 and less than 0.85, with about 5% households in the limited model. 17% households operate with a technical efficiency score below 0.80 in the unlimited model, with 35% in the limited model. Once again, we can see that the grassland NPP can greatly affect technical efficiency. Therefore, the possibility of increasing livestock grazing technical efficiency in the Sanjiangyuan region by an average of 10% can be achieved in the short term by adopting the practices of the best performing households.

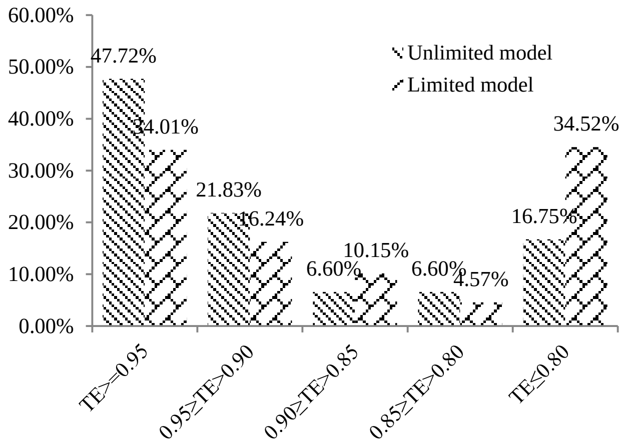

Figure 1. Range distribution of technical efficiencies

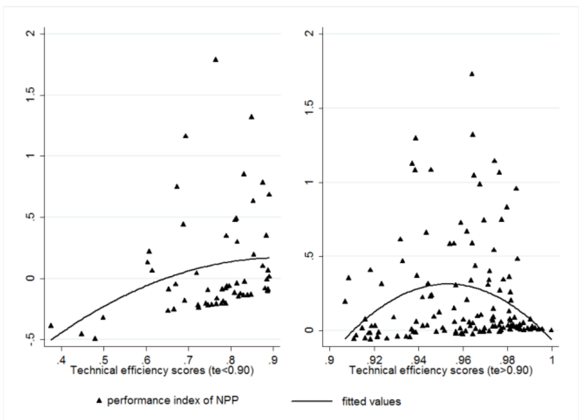

Figure 2. Scatter of EPI group on technical efficiency

4.3 Ecological performance index and ecological efficiency

The ecological performance indicator is defined to be the ratio of the technical efficiency from the unlimited model to the technical efficiency from the limited model in this study.

Therefore when EPI > 0, the technical efficiency in the stochastic distance function incorporating grassland NPP is bigger than that from the stochastic distance function which doesn't incorporate grassland NPP, which also implies the grassland NPP would enhance the livestock grazing potential. The mean of EPI is about 0.17 (table 4) and there are 65% of yak rearing households where EPI > 0, with the percentage for EPI < 0 approximately 35% (Table 5). After classifying the household into two groups according to whether the EPI > 0 (Table 6), the mean of the technical efficiency for households with EPI > 0 is 0.93, greater than that of 0.84 for households whose EPI < 0. Because the mean of the technical efficiency in the unlimited model is about 0.90, we have drawn a scatter graph of EPI of grassland NPP against technical efficiency (Figure 2). For the household with a technical efficiency which is lower than the mean level, we can see that the higher the EPI is, the greater the technical efficiency; whereas the relationship between EPI and technical efficiency is actually an inverse-U shape for households whose technical efficiency is higher than the mean lever 0.90. This might mean that the roles of grassland NPP in the production function and technical inefficiency model are more positive for lower technical efficiency households, which also implies that grassland NPP tends to be less important for households with comparatively higher technical efficiencies. The ecological efficiency is estimated based on the unlimited model; the mean is estimated to be 0.83 in the unlimited model (Table 5). From the summary of EE by group on whether EPI > 0 or EPI < 0 (Table 6), we can see that the means of ecological efficiency for households with EPI > 0 and EPI < 0 are very similar to each other. From the distribution of the two-way graph of the ecological performance indicator of grassland NPP (EPI) against the ecological efficiency, the relationship between ecological efficiency and EPI demonstrates that the higher the EPI is, the lower the ecological efficiency will be.

5. Conclusion and discussion

Incorporating ecological variables into the production function is a new step toward ecological efficiency or environmental efficiency analysis under the field of productivity and efficiency analysis. Findings of how ecological variables such as grassland NPP affect the production potential and technical inefficiency of livestock grazing in this study would be helpful for the development of scientific strategies and programs for local economic development and environmental protection, as well as for effectiveness of ecological protection projects, such as "returning pasture to grassland" in the Sanjiangyuan region. This paper measures the technical efficiency, ecological performance indicator and ecological efficiency of livestock grazing using a multi-outputs and multi-inputs stochastic input-oriented distance function by comparison of an unlimited model incorporating grassland NPP and a limited model which doesn't incorporate the grassland NPP variable. The average technical efficiency in the unlimited model is estimated to be 0.90, implying that the cost of livestock grazing can be decreased by 10% without any reduction of outputs. The ecological efficiency is estimated to be 0.80, averaged for all households, whereas the average EPI is about 0.83.

The variable NPP grassland plays a significant role in the stochastic distance function and technical inefficiency model, a role which is more positive for households with lower technical efficiency. This also implies that grassland NPP tends to be less important for households with comparatively higher technical efficiencies. A high ecological efficiency means overuse of grassland NPP, which in turn leads to grassland deterioration. The measurement of ecological efficiency can provide some important information for the government's environmental management policies. The tradeoff between traditional livestock grazing production and environmental protection calls scientific research of how to improve production potential under the sustainable grassland use.

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