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Balancing economic revenue and grazing pressure of livestock grazing on the Qinghai–Tibetan–Plateau

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Treating grazing pressure as an undesirable output of livestock grazing in a directional distance function improves understanding of how economic behaviour affects the environment. Field survey data from 193 livestock grazing households combined with remotely sensed net primary productivity (NPP) data on the Qinghai–Tibetan–Plateau was used to develop a directional output-orientation distance function. The average efficiency of livestock grazing households is 0.817 when incorporating grazing pressure as an undesirable output, which means that households can achieve 18.3% more output and decrease proportional grazing pressure holding all inputs fixed. The relative shadow price of undesirable grazing pressure to good output grazing revenue is estimated to be between 1.795 and 3.986. According to the Morishima elasticity of substitution between inputs, there is a significant complementary relationship between grassland, labour and capital.

Key words: directional distance function, Morishima elasticity of substitution, shadow price, technical efficiency.

1. Introduction

Concerns about environmental problems caused by economic development in developing countries have received much attention in recent years. Grassland is one of the main land uses globally and is essential for livestock grazing and grassland ecosystem services; how to find a balance between livestock grazing and grassland sustainability has been a major focus for research (De Haan *et al*. 1997; White *et al*. 2000; McDowell 2008). Demand for livestock products is growing rapidly in particular in emerging economies, driven by population growth, economic growth and expanding urbanisation. This has resulted in increasing grazing pressure on the grasslands, leading to overgrazing and grassland degradation (Li and Huntsinger 2011).

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Overgrazing occurs when the livestock stocking rate, or livestock per unit area per unit time, exceeds the capacity of the grassland to sustainably produce good quality forage (Vallentine 2000). It threatens the long-term use of grasslands in both economic and ecological terms and can result in grassland degradation, such as soil and productivity loss, increases in populations of undesirable plants and bare soil. Three quarters of the world's grazing lands are considered to be degraded to the extent that they have lost more than 25% of their capacity to support animals (UNEP 2005). Grazing pressure, measured as the ratio of livestock live weight divided by grassland forage biomass at a given point in time, results from increasing livestock stocking rates. This research was focused on analysing the effects of livestock grazing by adopting grazing pressure as an index of undesirable by-product from livestock grazing.

Modelling undesirable outputs (referred as "bad outputs" or "bads" in some studies) during production process has increased in the last two decades, especially in measurement of environmental performance of production units (Färe and Primont 1996; Yang *et al.* 2008; Picazo-Tadeo *et al.* 2014). Before the development of directional distance function analysis, many studies treated the undesirable outputs as inputs in the production function (Pittman 1981; Reinhard *et al.* 1999; Marchand and Guo 2014), on the basis that producing fewer undesirable outputs is just as preferable as to use fewer inputs. In some studies, undesirable outputs were called "reverse outputs" because their magnitude had an opposite effect to that of a good output (Lewis and Sexton 2004). Another approach to dealing with undesirable outputs is the transforming method, for example taking the reciprocal of undesirable outputs or subtracting them from some large-enough numbers, and then introducing them as good outputs (Lovell *et al.* 1995).

For modelling technology producing undesirable output, two axioms are required for outputs: null-jointness and weak disposability (Färe *et al.* 2005). Null-jointness requires that good outputs can only be produced if some undesirable output is produced. Conversely, no undesirable output produced means no good output can be produced. Weak disposability requires that simultaneous reduction of good output and undesirable output is feasible, which means there is cost to reduce production of undesirable output. However, there is a reverse U-shape relationship between cumulative grazing pressure and livestock production per unit area grassland according to McDowell (2008), where the livestock production per unit area increases with cumulative grazing pressure until the criteria value, and then begins to decline at the critical cumulative grazing pressure. Surprisingly, the reverse U-shape relationship pattern is consistent with directional distance frontier graph (Figure S1). Theoretically speaking, grazing pressure meets the regularity conditions of undesirable output. Empirically, grazing pressure is an ecological index for expressing the influence from human being activity grassland grazing on environment, which makes it reasonable to introduce grazing pressure as undesirable by-product from grassland grazing.

The directional distance function approach to efficiency measurement was first proposed by Chung *et al*. (1997) and Chambers *et al*. (1998) based on Shephard (1970). It has gained popularity over the last 10 years (Serra *et al*. 2011; Färe and Karagiannis 2013; Feng and Serletis 2014; Tang *et al*. 2016). The directional distance function allows for directional efficiency measurement; that is, the researcher is not limited to the commonly employed efficiency concept of simultaneous proportional reductions in inputs or expansion of outputs. A common use of directional distance analysis is the modelling of technologies that produce pollution as a by-product, such as electric utilities producing electricity and air pollution (Atkinson and Dorfman 2005; Murty *et al*. 2007; Cuesta *et al*. 2009; Coelli *et al*. 2013; Wang *et al*. 2013; Yao *et al*. 2015), and dairy farms producing polluted runoff (Reinhard *et al*. 1999; Fernandez *et al*. 2002; Sauer and Latacz-Lohmann 2014; Njuki and Bravo-Ureta 2015). To evaluate environmental goods such as air pollution emissions, soil pollution, environmental pressure or ecological diversity loss from human economic activity, relative shadow prices of nonmarket goods can be derived from the distance function.

The relatively novel framework of using directional distance function by treating the grazing pressure as an undesirable output combined with remotely sensed net primary productivity (NPP) data on the Qinghai–Tibetan–Plateau underpins this study to better understand grassland resource overuse. The Qinghai–Tibetan Plateau is a region heavily affected by advancing grassland degradation over wide areas, with overgrazing as one of the main drivers (Zhou *et al*. 2006; Akiyama and Kawamura 2007; Zhang 2008; Harris 2010). In this analysis, we employ a unique data set from a household survey of 193 households focused on livestock grazing in yak production on the Qinghai–Tibetan plateau. We calculate grazing pressure as the ratio between livestock live weight and total grassland NPP, where total grassland NPP is used to be representative of grassland biomass (Huang *et al*. 2016). We derive shadow prices of grazing pressure to grazing economic revenue, and elasticity of complementary or substitutionary relationships among inputs. Integrating grassland grazing pressure and economic revenue analysis to the valuation of livestock grazing would lead to better understanding the relationship between grazing pressure and production revenue, and thus, the research can be instructive for policy makers to improve local policies implemented on the Qinghai–Tibetan Plateau for enhancement of herder livelihood and environment protection.

2. Methodology and empirical model specification

A multiinput multioutput directional distance function incorporating grazing pressure as the undesirable output is developed in order to measure the production performance of grassland grazing within the framework of environmental efficiency. Following Chambers *et al*. (1998), Chambers (2002) Färe and Grosskopf (2000) and Färe *et al*. (2005), we first build the output-oriented directional distance function. The advantage of the output-oriented directional distance function is that it allows us to expand the desirable output while contracting the undesirable output holding inputs fixed, as shown in Figure S1. Assuming point A is the production point of a household, then the household improves production along the directional vector $g = (g_y, -g_b)$, that is adding ϑg_y to desirable output y while subtracting ϑg_b from the undesirable output b. The directional distance function is shown as Equation (1):

$$\overrightarrow{D_o}(x, y, b; g_y, -g_b) = \sup\{\vartheta : (y + \vartheta g_y, b - \vartheta g_b) \in P\} \tag{1}$$

To satisfy the translation property, it can be denoted as Equation (2):

$$\overrightarrow{D_o}(x, y, b; g_y, -g_b) - \vartheta = \overrightarrow{D_o}(x, y + \vartheta g_y, b - \vartheta g_b; g_y, -g_b) \tag{2}$$

We parametrically estimate the directional distance using stochastic estimation methods following Kumbhakar and Lovell (2000), when $\overrightarrow{D_o}(x, y, b; g_y, -g_b)$ is assumed to be 0 and error term $\varepsilon_i = v_i - u_i$ is added, so that the empirical stochastic specification form based on Equation (2) is written in Equation (3):

$$-\vartheta_i = \overrightarrow{D_o}(x, y + \vartheta g_y, b - \vartheta g_b; g_y, -g_b) + v_i - u_i \tag{3}$$

Assuming $g = (g_y, -g_b) = (1, -1)$, the quadratic form for our case, involving 4 inputs (x) and 1 good output (y) and 1 bad output (b), is denoted by Equation (4):

$$\begin{aligned}\overrightarrow{D_o}(x, y, b; g_y, -g_b) &= \overrightarrow{D_o}(x, y, b; 1, -1) \\ &= \alpha_0 + \sum_{k=1}^{4} \alpha_k x_k + \beta_1 y + \beta_2 b + \frac{1}{2}\sum_{k=1}^{4}\sum_{l=1}^{4} \alpha_{kl} x_k x_l \\ &\quad + \frac{1}{2}\beta_{11}(y)^2 + \frac{1}{2}\beta_{22}(b)^2 + \sum_{k=1}^{4} \gamma_{k1} x_k y + \sum_{k=1}^{4} \gamma_{k2} x_k b + \delta y b\end{aligned} \tag{4}$$

To fulfil the translation property and symmetry conditions, the required restrictions are:

$\beta_1 - \beta_2 = -1$, $\beta_{11} = \beta_{22} = \delta$, $\gamma_{k1} = \gamma_{k2}$, $k = 1, 2, 3, 4$.
$\alpha_{kl} = \alpha_{lk}$, $k = l = 1, 2, 3, 4$.

In our case, we impose these restrictions by choosing $\vartheta_i = b_i$, so that the quadratic form of the empirical specification for grassland grazing is as follows:

$$\begin{aligned} -b_i &= \overrightarrow{D_o}(x, y+b, 0) + v_i - u_i \\ &= \sum_{k=1}^{4} \alpha_k x_k + \beta_1 y^* + \frac{1}{2}\sum_{k=1}^{4} \alpha_{kk}(x_k)^2 + \frac{1}{2}\beta_{11}(y^*)^2 + \sum_{k=1}^{4}\sum_{l=1,k\neq l}^{4} \alpha_{kl} x_k x_l \\ &+ \sum_{k=1}^{4} \gamma_{k1} x_k y^* + v_i - u_i \end{aligned} \tag{5}$$

where $y_i^* = y_i + b_i$. y_i describes the desirable output of grassland grazing, b_i denotes the undesirable output, X is the vector of inputs x_k with x_1 = grassland area size, x_2 = labour, x_3 = household productive capital and x_4 = initial yak stock, v_i is a random error term, intended to capture events beyond the control of the herdsman, and u_i is a non-negative random error term, intended to capture technical inefficiency in production. In order to compare different effects of the directional vector, we use $g = (g_y, -g_b) = (1, -1)$ and $g = (g_y, -g_b) = (1, 0)$ in empirical analysis, where setting $g = (1, 0)$ means ignoring the change of grazing pressure in the production process to justify the relationship between good output revenue and bad output grazing pressure, we use a quantile regression estimator on a stochastic radially distance function, similar to the analysis of Gregg and Rolfe (2016).

The technical inefficiency model referred to Equation (6) is written as:

$$\mu_i = \tau_0 + \sum_{c=1}^{8} \tau_c * Z_{ci} \tag{6}$$

where Z is a vector of explanatory variables associated with the technical inefficiency effects. In addition to the one-step approach of directional stochastic frontier analysis on the determinants for technical inefficiency, a quantile regression estimator regressing on different quantile of technical efficiencies is used to check whether households adopt homogenous technology (Daouia and Simar 2007).

2.2 Relative shadow prices and the Morishima elasticity of substitution

Based on duality between the output distance function and the revenue maximisation function, shadow prices for nonmarket goods can be derived (Shephard 1970; Färe and Primont 1996). Application of Shephard's lemma gives the corresponding shadow prices:

$$\nabla_x \vec{D}(x, y) = r^*(x, y) \tag{7}$$

where $r^*(x, y)$is the cost minimising input price vector.

Because the input prices are not available and optimal cost of production cannot be accurately estimated in this paper, we use relative shadow prices as shown in Equation (8):

$$R_{kl} = \frac{r_k^*}{r_l^*} = \frac{\partial \vec{D}(x, y)/\partial x_k}{\partial \vec{D}(x, y)/\partial x_l} \tag{8}$$

where r_k^* and r_l^* are the shadow prices of the inputs x_k and x_l, respectively. This ratio is the relative shadow price of input x_k with respect to input x_l. These shadow prices reflect the trade-off between different inputs (Hailu and Veeman 2000; Misra and Kant 2007; Murty *et al.* 2007; Rahman 2010).

The indirect Morishima elasticity of substitution (MES) can be computed according to Equation (9) (Blackorby and Russell 1989; Stern 2011):

$$\text{MES}_{kl} = -\frac{\partial \ln(\vec{D}_k/\vec{D}_l)}{\partial \ln(X_l/X_k)} = x_k \left(\frac{\vec{D}_{kl}}{\vec{D}_l} - \frac{\vec{D}_{kk}}{\vec{D}_k} \right) \tag{9}$$

where the subscripts on the distance functions refer to partial derivatives with respect to inputs. This represents the change in relative marginal products and input prices required to affect substitution under cost minimisation. High values reflect low substitutability, and low values reflect relative ease of substitution between the inputs (Morrison-Paul *et al.* 2000; Morrison-Paul and Nehring, 2005). The MES can be simplified as follows:

$$\text{MES}_{kl} = \varepsilon_{kl} - \varepsilon_{kk} \tag{10}$$

where ε_{kl} and ε_{kk} are the constant output cross and own elasticity of shadow prices with respect to input quantities.

The shadow price elasticities with respect to input quantities are given by:

$$\varepsilon_{kl} = (\alpha_{kl} + S_k S_l)/S_k \text{if } k \neq l \tag{11}$$

$$\varepsilon_{kk} = [\alpha_{kk} + S_k(S_k - 1)]/S_k \text{if } k = l \tag{12}$$

where S_k is the first-order derivatives of the distance function with respect to input x_k, that is:

$$S_k = \partial \vec{D} / \partial x_k \tag{13}$$

3. Data descriptive statistics

The social-economic data used in this paper was drawn from field survey data in southern Qinghai province conducted by the Center for Chinese Agricultural Policy (CCAP) of the Chinese Academy of Sciences in August and October 2012. The net primary production data is from the MODIS GPP/NPP Project. The case study region is the Sanjiangyuan region in China, known as the Three-River Headwaters in English. It is located in the north-eastern Qinghai–Tibetan Plateau, where more than 90% of the local people are of Tibetan Ethnic Minority. The stratified random sampling method was used to select observations and 193 of them were available for this analysis. As grassland grazing on the Tibetan Plateau still is largely the traditional half-nomadic pastoral system (Davies and Hatfield 2007; Harris 2010), prices for input and outputs are generally unavailable. Household labour and products are often traded directly as barter rather than through formal markets, which is advantageous for establishing the production function as price variables are not necessarily required.

Classic inputs are aggregated into four categories (grassland area, labour, capital and initial yak), and outputs are aggregated into two categories (y as the desirable output of revenue from grassland grazing and output b, the undesirable output of grazing pressure). There are two kinds of pastures on the Qinghai–Tibetan Plateau: summer/autumn pasture and winter/spring pasture, where grassland area (x_1) is the sum of summer pasture area and winter pasture area for each household. The grassland is divided and contracted to each household individually, so grazing lands are not open accessed, and there is no common grazing land. In our data set, more than 60% of households have fenced pastures, livestock shelters and plots for hay and forage production in the corrals. Labour (x_2) consists of family labour, measured by person. Capital (x_3) consists of productive machinery (irrigation machine, transportation machine and so on). Initial yak stock (x_4) means the initial yak input at the beginning of the year and is calculated by multiplying the average weight of a yak by the number of yaks in each household. Desirable output y denotes the revenue of yak meat produced in the year and revenue of the other outputs, including the revenue from Tibetan sheep meat, output of milk, yak hide, Tibetan sheep wool and so on. Undesirable output b denotes the grazing pressure of livestock grazing on the Qinghai–Tibetan Plateau.

Grazing pressure is international terminology for the relationship between animal live weight and forage mass per unit of grassland on grazed land at a specific time (Allen *et al.* 2011). Grazing pressure is highly positively correlated with the overgrazing ratio: the more the livestock stocking rate increases, the higher the grazing pressure at a point in time. The grassland of the Qinghai Province of China, one of the largest grasslands in China, has been found by researchers to have a high level of overgrazing by comparing the actual to what is believed to be the proper livestock stocking rate (Fan *et al*. 2011; Zhang *et al*. 2014). Assuming the suggested "proper carrying capacity" or stocking rate of Zhang *et al*. (2014) is the appropriate baseline, the overgrazing ratio estimated from the field survey was found to be more than 300%, indicating that overgrazing persists.

As grazing pressure is the animal-to-forage ratio, we calculate grazing pressure as the ratio between livestock live weight and grassland biomass, $\text{grazing pressure} = \frac{\text{livestock live weight}}{\text{grassland biomass}}$, where grassland total NPP is used as a proxy for grassland biomass in this study and thus $\text{grazing pressure} = \frac{\text{livestock live weight}}{\text{grassland total NPP}}$. Grassland total NPP is computed by multiplying unit NPP by the total grassland area. Unit NPP (measured with 1000 kgC/ha) is computed with daily MODIS land cover, FPAR/LAI and global GMAO surface meteorology at 1 km for the global vegetated land surface (Zhao and Running 2010). These variables provide the initial calculation for growing season and carbon cycle analysis and are used for agriculture, range and forest production estimates. After matching the rough boundary of summer pasture and winter pasture to the 1 km NPP raster data file, and getting samples of NPP for each pasture according to the pasture area, we summarise the NPP of pastures for each grazing household.

For the technical inefficiency model, operational and farm-specific variables were considered including the total NPP change of each household's pasture (z_1), household size (z_2), distance from fixed home to summer pasture (z_3), grazing experience (z_4), summer pasture area (z_5) and winter pasture area size (z_6), a dummy variable for pasture plot (z_7) and a dummy variable for whether there is leased-in grassland from other households (z_8). The total NPP change for each household (z_1) is calculated by subtracting total NPP in the year 2011 from total NPP in the year 2012. Household size (z_2) is the number of people in the household. Distance from fixed home to summer pasture (z_3) measures the geographic distance from the fixed home to the summer pasture. Grazing experience (z_4) denotes how many years of grazing experience each household head has. Summer pasture area (z_5) and winter pasture area (z_6) are pasture area size in summer and winter, respectively, while the dummy variable for pasture plot (z_7) indicates whether the summer pasture and winter pasture are located in the same plot or adjacent plots. The dummy variable for lease-in grassland (z_8) equals 1 if the household uses leased-in grassland from other households, and 0 for otherwise. In order to interpret the estimated first-order parameters as partial production elasticities at the sample mean, we divide the output and input variables by their respective sample means. A statistical description of the variables is shown in Table 1.

4. Results

Before presenting the performance of inputs and outputs in the directional distance function, we compared the directional distance functions with different assumptions of directional vectors $g = \left(g_y, -g_b\right) = (1, -1)$ and $g = \left(g_y, -g_b\right) = (1, 0)$ (Table S1). We assigned model 1 with directional vector $g = (1, -1)$, denoting the expansion of desirable output while subtracting the undesirable output of grazing pressure. In model 2, $g = (1, 0)$ is assumed, denoting the expansion of desirable output without subtracting the undesirable output of grazing pressure. A Hausman test is used to compare the two models with a null hypothesis that there are no systematic differences between the two. From the Hausman test in the bottom of Table S1, we can see the null hypothesis is strongly rejected, indicating that there are systematic differences between the estimates of the two models. Taking into account the estimated coefficients signs and monotonicity conditions, model 1 is preferred over model 2. Hereafter, all analysis and estimates will be based on model 1 with directional vector of $g = \left(g_y, -g_b\right) = (1, -1)$. The δ_u is estimated to be 0.586, which means the inefficiency term u_i should not be ignored, which supports us in setting the directional distance function combined with technical inefficiency model, as

Table 1 Descriptive statistics of variables used in the study

Variable Description	Symbol	Measurement Unit	Mean	SD
Inputs variables				
Grassland area size	x_1	μ†	937.378	1413.141
Labour	x_2	person	2.308	1.273
Productive capital	x_3	1000yuan	129.210	186.870
Initial yak at the beginning of 2011	x_4	1000 kg	7.170	8.150
Outputs variables				
Good output: revenue from livestock grazing	y	1000yuan	105.260	112.020
Bad output: grazing pressure	b	–	0.212	0.279
Household characteristics variables				
Total NPP change in 2011	z_1	1000 kg	4.940	13.570
Household size	z_2	head	4.720	1.672
Distance from fixed home to summer pasture	z_3	km	15.240	19.680
Grazing experience	z_4	year	29.865	11.971
Summer pasture area	z_5	1000 μ	542.985	911.036
Winter pasture area	z_6	1000 μ	395.652	649.293
		No. of dummy = 1	No. of dummy = 0	
Dummy variable pasture plot (1 = the winter pasture and summer pasture are different plots; 0 = other)	z_7	44	149	
Dummy variable of whether there is leased-in grassland (1 = yes; 0 = no)	z_8	43	150	

Note: †Conversion rate 1 ha = 15 μ.

showed in Table 2, where the likelihood value is −3.554 with degree of freedom 31. The likelihood ratio test for model 1 and model 2 implies that the application of the technical inefficiency model would definitely improve the model specification. Likelihood ratio tests results for the selection of the technical inefficiency model are reported in Table S2. According to all the likelihood ratio tests and one-sided inefficiency random components values, we choose the preferred model in Table 2 and consequently calculate the first-order conditions, shadow price and Morishima elasticity of substitutions.

4.1 Parameter estimates of directional distance functions

The one-step approach for both the directional distance function and technical inefficiency model using maximum likelihood is presented in Table 2, with all variables divided by mean. Most coefficients are statistically significant; in particular, all parameter estimates involving the good output y. The directional output distance function is concave in outputs; thus, $\partial^2\left(\overrightarrow{D_o}(x,y,b;1,-1)\right)/\partial y = \beta_{11} \leq 0$, and according to the restrictions implied by the translation property, $\partial^2\left(\overrightarrow{D_o}(x,y,b;\right.$

Table 2 Estimates of directional stochastic distance function and technicalinefficiency model

Variables	Coef.	SE	Variables	Coef.	SE
Stoc. frontier normal/half-normal function			Technical inefficiency function		
Dependent variable: - ϑ			Dependent variable: lnsig2u		
Constant	0.084	0.098	Constant	−4.358***	1.662
x_1	0.197**	0.096	z_1	−0.265***	0.081
x_2	−0.300**	0.135	z_2	1.176**	0.548
x_3	0.097	0.059	z_3	−0.348	0.212
x_4	−0.063	0.113	z_4	−1.058*	0.595
y^*	−0.639***	0.059	z_5	−0.016	0.174
$0.5\cdot x_1{}^2$	−0.069***	0.016	z_6	1.033***	0.208
$0.5\ x_2^2$	0.263**	0.110	z_7	1.781	1.258
$0.5\cdot x_3^2$	−0.105***	0.020	z_8	−1.947***	0.543
$0.5x_4^2\cdot$	−0.152***	0.049			
$0.5\cdot y^{*2}$	−0.071***	0.013			
$x_1\cdot y$	0.485***	0.031			
$x_2\cdot y$	−0.076**	0.036			
$x_3\cdot y$	−0.092***	0.014			
$x_4\cdot y$	0.105***	0.020			
$x_1\cdot x_2$	−0.075	0.069			
$x_1\cdot x_3$	0.023	0.022			
$x_1\cdot x_4$	−0.409***	0.058	Log likelihood = −3.554		
$x_2\cdot x_3$	0.134***	0.041	Number of observation = 193		
$x_2\cdot x_4$	0.214***	0.071	Wald $\chi^2(20)$ = 5807.730		
$x_3\cdot x_4$	0.157***	0.025	Prob. > χ^2 = 0.000		
Idiosyncratic error variance function					
Constant	−3.681***	0.231			

Notes: *Significant at 10% level ($P < 0.10$), **significant at 5% level ($P < 0.05$), ***significant at 1% level ($P < 0.01$).

$1,-1))/\partial b = \partial^2\left(\overrightarrow{D_o}(x,y,b;1,-1)\right)/\partial y\partial b = \beta_{11}$, β_{11} is estimated to be -0.071, significant at the 1% statistical level.

Based on the estimates from the directional distance function, the elasticities of the directional distance function with respect to inputs and outputs are calculated to get a full understanding of the performance of inputs and outputs in the grassland grazing process, and elasticities of the sample mean are presented (Table 3). The t-test is used to test whether the elasticities are different from zero at the 10% statistical level. The monotonicity condition of the directional distance function requires $\partial\left(\overrightarrow{D_o}(x,y,b;1,-1)\right)/\partial x \geq 0$. With the exception of input x_4, the initial yak at the beginning of the year, elasticity of distance with respect to inputs grassland area size, labour and capital have expected positive signs, implying that increasing the input of any of these inputs will increase production potential substantially. The largest elasticity of the directional distance with respect to inputs comes from the grassland area, which is estimated to be 0.637, implying a 1% increase of grassland area would enhance production potential by 0.637%. The monotonicity conditions of the directional distance function for outputs require $\partial\left(\overrightarrow{D_o}(x,y,b;1,-1)\right)/\partial y \leq 0$ and $\partial\left(\overrightarrow{D_o}(x,y,b;1,-1)\right)/\partial b \geq 0$. The elasticity of distance with respect to desirable output ε_y is -0.359, and the elasticity of undesirable output grazing pressure ε_b is estimated to be 0.641; both are significant at the 1% statistical level. A 1% increase in desirable output would involve reducing the distance by 0.359%, while a 1% increase in the undesirable output, grazing pressure, would involve expanding the distance by 0.641%. This means it is possible to achieve higher productivity with lower grazing pressure, thus leading to more efficient use of the available grassland resource.

4.2 Shadow price of grazing pressure

As grazing pressure cannot be traded in the market directly, the relative shadow prices of grazing pressure to revenue of livestock grazing are calculated for a better understanding of their relationship with each other. The relative shadow price of grazing pressure is estimated to be 1.795 at the

Table 3 Elasticity of distance with respect to inputs and outputs

Elasticity	Mean	SD	Min.	Max.
Inputs elasticity				
ε_{x1}	0.637***	0.677	−0.730	3.933
ε_{x2}	0.084***	0.326	−1.017	1.666
ε_{x3}	0.122***	0.177	−0.709	0.570
ε_{x4}	−0.042	0.644	−6.080	1.636
Outputs elasticity				
ε_y	−0.359***	0.730	−1.508	6.579
ε_b	0.641***	0.730	−0.508	7.579

Notes: T-test for elasticity different from 0, *significant at 10% level ($P < 0.10$), **significant at 5% level ($P < 0.05$), ***significant at 1% level ($P < 0.01$).

sample mean, which means the "price" coming from grazing pressure is higher than production of one unit of good output. As there is no reason to interpret a shadow price for observations that violate monotonicity conditions (Färe *et al*. 2005), we summarise the relative shadow price for a partial sample which meets the monotonicity conditions in the third column of the upper part in Table 3. Thus, we can see that the relative shadow price of grazing pressure is 3.986. The interpretation of the shadow price of grazing pressure is the revenue value of good products that must be foregone in order to reduce the grazing pressure by one unit when all inefficiency has been eliminated and the grazing household produces on the production frontier. In previous literature on environmental efficiency analysis, most of the studies of shadow prices of environmental outputs were assumed to be negative (Färe *et al*. 1993, 2005; Hailu and Veeman 2000), which means that these environmental outputs are "undesirable outputs". Notable results include the significant negative estimates from grazing pressure on economic revenue in quantile regression of radially distance function effects, which justify the use of grazing pressure as a 'bad' output.

Marginal products of grazing pressure on revenue are significant when estimated across different quantiles (Figure 1), where the pattern indicates that lower quantiles of revenue are associated with greater absolute values of marginal products of grazing pressure. The value of MES_{by} is estimated to be −0.552 for all samples and −0.728 for partial samples which meet the monotonicity condition (Table 4). The MES_{by} measures the ability of the grazing household to trade reductions in revenue output to abate grazing pressure. A large negative MES_{by} indicates a large change in the relative shadow price of grazing pressure for the desirable output of livestock revenue, thus resulting in a greater abatement cost to reduce grazing pressure.

4.3 Morishima elasticity of substitution between inputs

MES can be used to measure changes in relative output and input quantities as a consequence of changes in relative prices (Färe *et al*. 2005; Sauer and

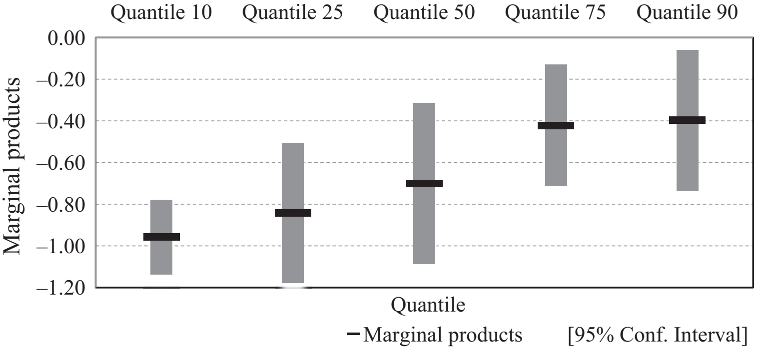


Figure 1 Marginal products of grazing pressure on economic revenue.

Table 4 Relative shadow price and Morishima elasticity of substitution

Outputs perpective				
Variable			Full sample (Obs. = 193)	Partial sample (Obs. = 173)
Relative shadow price: $\frac{\partial \vec{D}(x,y,b)/\partial y}{\partial \vec{D}(x,y,b)/\partial b}$			1.795	3.986
MES_{by}: Morishima elasticity substitution of b to y			−0.552	−0.728

MES(row, column)		Inputs perpective			
		x_1 Grassland area	x_2 Labour	x_3 Capital	x_4 Initial yaks
x_1	Grassland area	–	0.431***	0.706***	−0.496***
x_2	Labour	0.747	–	0.731***	0.755***
x_3	Capital	2.067***	1.992**	–	1.965**
x_4	Initial yaks	1.021	2.066	1.960	–

Notes: T-test for elasticity different from 0, *significant at 10% level ($P < 0.10$), **significant at 5% level ($P < 0.05$), ***significant at 1% level ($P < 0.01$).

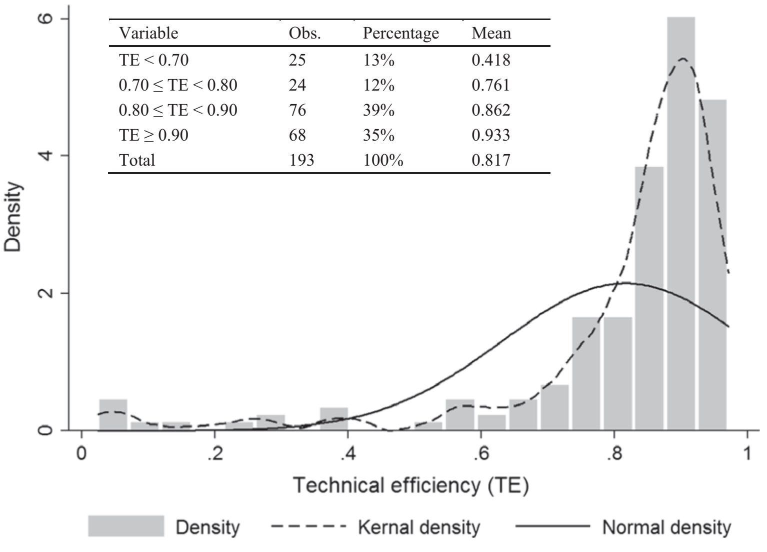
Latacz-Lohmann 2014). Using Equations (11) to (15), we calculate MES for substitution or complementarity relations among inputs based on estimates of the directional output distance function (lower part of Table 4). A positive MES indicates a complementary relationship between two inputs, and a negative MES indicates a substitutionary relationship between inputs; in terms of absolute values of MES, high values reflect a low degree of complementarity or substitutability and low values reflect a high degree of complementarity or substitution between the inputs (Blackorby and Russell 1989; Morrison-Paul *et al.* 2000; Rahman 2010). Most of the elasticities are positive and are significantly different from zero, as shown by the t-tests. An exception is the substitution elasticity between the grassland area size and the initial livestock stock which is equal to −0.496; there are further complementary relationships among other combinations.

4.4 Estimates for the inefficiency model and efficiency analysis

According to the general-to-specific modelling method (Hendry 1980), we first estimate a model including all control variables, and then, we drop the least significant variables according to a likelihood ratio test and estimate the model again. This procedure is repeated until only variables that are significant enough to pass the likelihood ratio test at the 10% level remain. The final determinants for the variation in a grazing household's technical inefficiency are estimated in the technical inefficiency model (right part of Table 2).

Total grassland NPP change (z_1) is estimated to be negative in relation to technical inefficiency, −0.265, significant at the 1% statistical level. This indicates that a decrease in grassland NPP leads to an increase in household efficiency. However, as the total NPP change might be assumed to be consumed by livestock, implying that the more the total NPP changes, the greater the trend towards it being overgrazed. Household size (z_2) is estimated to be positively related to technical inefficiency. There is no significant effect of distance from the fixed home to the summer pasture (z_3) on inefficiency, but it is suggested that this variable should be kept in the model by a general-to-specific process. More grazing experience would increase technical efficiency, as shown from estimates of grazing experience (z_4), -1.058. We treat summer pasture area (z_5), winter pasture area size (z_6) and the dummy variable of pasture plot (z_7) as a variable block, where we can see that winter pasture area size is positively related to technical inefficiency, 1.033, significant at the 1% statistical level. The dummy variable for lease-in grassland (z_8) has a highly positive affect on technical inefficiency, which means leasing in grassland from other households increases technical efficiency.

We calculate each household's technical efficiency after estimation of the stochastic distance function and technical inefficiency model. The average estimated technical efficiency is 0.817 (Table within Figure 2), which indicates that on average, grazing households can improve technical efficiency by 18.3% in terms of expanding livestock revenue and reducing grazing pressure given unchanged inputs. The distribution of technical efficiencies seems satisfactory from the histogram graph (Figure 2), and we can see that about 13% of the households have a technical efficiency lower than 0.70, whereas 12% of households have efficiency ≥0.70 and <0.80; 39% of households have



Variable	Obs.	Percentage	Mean
TE < 0.70	25	13%	0.418
0.70 ≤ TE < 0.80	24	12%	0.761
0.80 ≤ TE < 0.90	76	39%	0.862
TE ≥ 0.90	68	35%	0.933
Total	193	100%	0.817

Figure 2 Histogram graph of technical efficiency.

efficiency ≥0.80 and <0.90; and 35% households operate with a technical efficiency larger than 0.90.

5. Conclusion and discussion

Incorporating grazing pressure as the undesirable output from livestock grazing using the directional distance function is a new step towards environmental efficiency analysis in the field of productivity and efficiency analysis. The environmental variable, grazing pressure, representing the undesirable output from livestock grazing, plays a significant role in the directional distance function and technical inefficiency model. The average technical efficiency is estimated to be 0.817, implying that grassland production potential can be increased by 18.3% with directional adjustment of reduction in grazing pressure. There is space to increase the production potential of livestock grazing without increasing the grazing pressure by adjusting grassland size, labour and capital.

The findings of our study show that livestock grazing is probably operating with a high ecological risk status. Although there is a reverse U-shape relationship between cumulative grazing pressure and livestock production per unit area grassland, the ecological risk is monotonously positively increasing as cumulative grazing pressure is increasing, which is strongly associated with overgrazing. A higher probability of ecological risk would result in a higher probability of grassland degradation (McDowell 2008).

Livestock grazing can have negative impacts on the environment if it is not kept within acceptable limits. The trade-off between traditional livestock grazing production and ecological protection of grassland calls for more scientific research on how to improve production potential with sustainable grassland use. We suggest implementing an efficient livestock grazing monitor policy to ensure an appropriate livestock stocking rate on the Qinghai–Tibetan Plateau. Understanding how environmental variables and grazing pressure affect the production potential and technical inefficiency of livestock grazing is helpful for the development of scientific strategies and programs for local economic development and environmental protection, as well as for the effectiveness of ecological protection projects.

There are a few limitations in this research that should be noted. For example, there is an assumption that the quality of livestock meat is homogenous for different livestock age groups. In terms of the approximate pasture boundary matching the long time period and large scale of remote sensing data to the household scale means there is inevitable measurement error to some extent. For the grazing pressure measurement, we have not considered the grazing pressure from wild stock (Fisher *et al.* 2004). The consideration of the impact of both domestic stock and wild stock for analysis of sustainable livestock grazing could be considered in future work when wild stock data are available.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1 Directional distance function with different directional vector.
Table S2 Hypothesis test for model selection.
Figure S1 Directional distance function.