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Land size and productivity in the livestock sector: evidence from pastoral areas in China*

Fang Xia, Lingling Hou, Songqing Jin and Dongqing Li†

This article explores the relationship between land size and productivity in the livestock sector. Household panel data from pastoral areas in northwestern China were analysed. Results suggest an inverse relationship (IR) between land size and the number of livestock per ha. IR can be largely explained by labour input intensity, which is negatively correlated with land size. We find that household's labour demand is not separable from household's labour supply and households' decisions to rent land and hire labour for grazing are significantly related to the labour–land endowment ratio. These findings are consistent with the Chayanovian explanation that labour input intensity varies with farm size due to unobserved interhousehold variation in shadow wage rates. In addition, participation in the labour market does not significantly influence the IR for the employer, while the practice of land renting reduces, but does not eliminate, the IR for the lease. These findings point towards the potential for using factor markets to optimise pasture-based livestock production scale, and the need to promote the factor market development to achieve efficiency in resource use.

Key words: China, grassland, inverse relationship, labour market, land rental market, livestock.

1. Introduction

Documented as early as the 1920s in Russia (Chayanov 1926), the inverse relationship (IR) between land size and land productivity is one of the longest standing topics in the agricultural economics literature and has attracted renewed interest in recent years (Carletto *et al*. 2013, 2015; Ali and Deininger

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†Fang Xia is Associate Professor at the Research Institute for Global Value Chains, University of International Business and Economics, Beijing, China. Lingling Hou (email: llhou.ccap@pku.edu.cn) is Assistant Professor and Dongqing Li is Research Assistant at the China Center for Agricultural Policy, School of Advanced Agricultural Sciences, Peking University, No. 5 Yiheyuan Road, Haidian District, Beijing, 100871, China. Songqing Jin is Associate Professor at the Department of Agricultural, Food and Resource Economics, Michigan State University, 446 West Circle Dr., Rm 202, East Lansing, MI, 48824, USA. Songqing Jin is Adjunct Professor at the China Academy for Rural Development, Zhejiang University, No. 866 Yuhangtang Road, Hangzhou, 310058, China.

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2015; Deininger *et al.* 2018; Desiere and Jolliffe 2018; Abay *et al.* 2019; Gourlay *et al.* 2019; Muyanga and Jayne 2019; Bevis and Barrett 2020). However, to the best of our knowledge, these studies have focused on the production of crops, leaving the IR issue in livestock production largely unstudied. If the IR is driven by factor market imperfections (Feder 1985; Barrett 1996; Ali and Deininger 2015; Deininger *et al.* 2018; Muyanga and Jayne 2019) rather than crop production factors, such as the edge effects due to behavioural mechanisms (Bevis and Barrett 2020) and the artefact of systematic misreporting of crop output (Desiere and Jolliffe 2018; Gourlay *et al.* 2019), it should also exist in livestock production. This article fills the gap in the literature by exploring whether there is an IR between grassland size operated by herders and the number of livestock per ha. In addition, since the IR is related to productivity, the article also sheds light on issues associated with China's growing consumption of high-value agricultural products (Pingali 2007; Rask and Rask 2011; Fukase and Martin 2016).

Livestock production systems in China are differentiated between pastoral and agricultural areas. Unlike gazing on open grassland in northwestern pastoral areas, households (backyard and specialised production) and commercial farms in agricultural areas usually integrate livestock production with cropping and provide grain-based diets to animals (Rae *et al.* 2006; Rae and Zhang 2009). It is inappropriate to examine the IR in agricultural areas, since the livestock production is only indirectly linked to land through crop production. Approximately 80 per cent of China's grasslands are located in arid and semi-arid regions with annual precipitation <500 mm. The nature of the fragile systems decides the traditional seminomadic pastoralism with very little external inputs (e.g. seedling, irrigation, haying) (Harris 2010) for almost all herders with different land sizes, providing us the opportunities to directly investigate the IR between land size and livestock productivity. Hence, our sample comprises herders living on the alpine meadows in Qinghai and Gansu who are not engaged in crop production. Panel data on livestock ownership and pastoral areas in 2008, 2009, 2010, 2015, 2016 and 2017 from a household survey conducted in 2017–2018 allow us to examine the IR with time-invariant household characteristics being controlled. We first examine whether or not, and to what degree, the IR exists in pastoral livestock production based on our data. If the IR exists, then we explore the underlying causes for the existence of IR. In particular, we will test for the presence of factor market imperfections, and if so, to what degree IR is affected by the conditions of the factor markets.

We find that the IRs between operated grassland size and the livestock ownership per ha measured in different ways can be largely explained by labour input intensity which is also negatively correlated with operated grassland size. This implies that the herders may fail to optimise their operations due to frictions in factor markets. To provide evidence, we test the separation hypothesis (Benjamin 1992) and examine whether the labour–land endowment ratio can explain decisions on participation in factor markets

(Barrett *et al*. 2008). Rejection of the separation hypothesis and the fact that the labour–land endowment ratio explains decisions of renting in land and hiring labour for grazing indeed point towards market imperfections. We also find that it is the herder's status in participating in the land rental market (not the labour market) that has a significant effect on IR. More specifically, while herders who rented in land show smaller IRs than the autarky households, those who rented out land show more significant IRs than the autarky households. But the magnitude of effect is extremely small for participation in either side of the labour market. On the one hand, this is consistent with optimising behaviour given transactions costs, and on the other hand, it points towards the potential to use the factor markets to achieve efficiency in use of resources.

The remainder of the article is organised as follows. The following section reviews the literature on the IR and relates the IR discussion to consumption of livestock products and livestock production in the context of China. Then, we introduce our sample, provide descriptive evidence on the IR, and present the empirical strategy. After this, we discuss the econometric results of the IR, the separation hypothesis and the role of the two factor markets. We finally conclude the article with policy implications.

2. Background

2.1 IR literature

The literature documents two levels of IR between land size and land productivity: farm level and plot level (Desiere and Jolliffe 2018). Farm-level IRs were first observed in Russia by Chayanov (1926) who attributes small farms' high productivity to their massive use of family labour. In line with this hypothesis, Sen (1962) explains that the combination of imperfect labour market and fixed land endowment causes farm-level IRs in India, where small farms use more family labour at a less-than-market wage rate. Feder (1985) demonstrates that IRs occur when imperfections in the land and labour markets are combined. IRs can also emerge if labour and credit market imperfections are combined with the fixed costs of production (Eswaran and Kotwal 1986). Barrett (1996) suggests that in the absence of labour market imperfections, those of the other markets can promote small farms to use family labour more intensively under the assumption of price uncertainty.

While factor market imperfection-induced IRs have been widely supported by empirical evidence in developing countries (Bardhan 1973; Berry and Cline 1979; Collier 1983), agricultural economists have also focused greatly on other possible causes for IRs, such as unobserved heterogeneity across farms. This may challenge the validity of such studies (Bhalla and Roy 1988; Benjamin 1995; Lamb 2003). Controlling for land quality and time-invariant household characteristics using plot-level data does not eliminate IRs (Assuncao and Braido 2007; Barrett *et al*. 2010), recent studies have attempted to explain plot-level IRs with respect to the edge effects due to behavioural mechanisms (Bevis and Barrett 2020) and the measurement errors (Carletto *et al*. 2013, 2015; Desiere and Jolliffe 2018; Abay *et al* 2019; Gourlay *et al*. 2019). Two strands of literature have used plot-level data to explain the persistent IRs in agricultural production. The first strand argues that smaller plots with larger periphery-to-interior ratios are more productive because farmers are more aware of the edges of plot and tender their edges more carefully and intensely. The second posits that IRs may be an artefact of farmers' systematic misreporting of land size and/or production. While the IR hypothesis remains valid with better measure of land size collected using GPS devices (Carletto *et al*. 2013, 2015), crop-cut production that corrects measurement error in self-reported production makes the IR disappear (Desiere and Jolliffe 2018; Gourlay *et al*. 2019). Combining self-reported and objective measures for both land size and production, Abay *et al*. (2019) show that the IR found in the self-reported data vanishes with more accurate measures and concludes that accounting measurement error in only one of the variables may worsen bias in estimated parameters.

Plot-level IR is less irrelevant to livestock grazing on open grassland for two reasons. First, as herders do not choose specific locations on their grassland for livestock to graze, the periphery-to-interior ratio should not affect productivity through behavioural mechanisms. Second, objective measure for production has not been widely used in agricultural surveys as GPS-measured land size.[1] Given calculating the number of livestock is much easier than calculating crop output, systematic misreporting of output in livestock production should not be as serious as crop production. Hence, if there is an IR between grassland size operated by herders and the number of livestock per unit area, imperfections in the factor markets are more likely to be the cause.

2.2 Consumption of livestock products and livestock production

Inverse relationships are a long-standing research question that has important policy implications (Collier and Dercon 2014), as they point towards Pareto inefficient resource allocation. In the case of China, the potential to enhance productivity by improving imperfections in the factor markets would have a far-reaching impact on the global market. According to the Food and Agricultural Organization (FAO), China is a leading country in livestock production, ranking fourth and first in the past decade in terms of the stock of cattle and the stock of sheep, respectively. However, induced by income growth and diet upgrades (Rask and Rask 2011), China's per capita consumption of beef and lamb (mutton) also increased from 2.6 kg in 2007 to

[1] For example, in all Living Standards Measurement Study-Integrated Surveys on Agriculture (LSMS-ISA), only in the case of Ethiopia, the output was physically measured by crop cuts.

3.3 kg in 2016 (National Bureau of Statistics of China 2013, 2017).[2] In addition to importing grain as feed, the FAO data suggest that China's net import of cattle meat increased from 3,986 tonnes in 2007 to 133,441 tonnes in 2016. In the same period, China's net import of sheep meat grew from 61,235 tonnes to 237,945 tonnes. It is, therefore, not surprising to see emerging debates on how China will be fed in the future (OECD and FAO 2013; Anderson and Strutt 2014; Fukase and Martin 2016). Modernization of China's food supply chain is suggested to be a useful effort (Pingali 2007; Waldron *et al.* 2010); increasing allocative efficiency of resources among producers through factor market improvement could be another important approach, as a way to offset the fact that the improvement of technical efficiency in China's livestock sector can be slow in spite of considerable technical innovation (Rae *et al.* 2006).

3. Data and estimation strategy

3.1 Data and descriptive statistics

To provide empirical evidence on IRs and the above-mentioned related issues, we conducted a household survey from October 2017 to January 2018 in 10 pasture-based livestock production counties (six in Qinghai and four in Gansu). Three townships were selected from each county, two villages were selected in each township, and six households were interviewed in each village. As a result, we obtained a total sample of 360 households. Information of the current period (year 2017) was complemented with recall data of 2008, 2009, 2010, 2015 and 2016. It allowed us to conduct a panel analysis in which household time-invariant characteristics were controlled. To avoid a potential bias arising due to a small number of herders grazing on village public grassland, these households were excluded from our sample. Hence, our effective sample size was of approximate 350 households for each year.

In addition to basic household and individual information, our survey included several modules to collect detailed information on livestock production at both household and plot levels. For practical reasons, information on livestock production, including livestock numbers by animal type, labour and various inputs, was mainly collected at the household level. On the other hand, information on land size, transactions and plot characteristics was surveyed at the plot level with GPS coordinates recorded. The GPS coordinates allowed us to combine important geographic

[2] The National Bureau of Statistics provided per capita consumption of beef and lamb (mutton) for rural residents and urban residents separately in 2007. Per capita consumption of beef and lamb (mutton) was 1.5 kg for rural residents and 3.9 kg for urban residents. China had 715 million rural residents and 606 million urban residents in 2007. So per capita consumption of beef and lamb (mutton) for all residents in 2007 was 2.6 kg versus 3.3 kg in 2016.

information, that is, monthly precipitation, that is simultaneously correlated with the grass quality and livestock production decisions. The monthly precipitation data were aggregated from daily meteorological data from the National Meteorological Information Center. For counties without a national station, a spatial interpolation method proposed by Thornton *et al.* (1997) was used to extrapolate the daily precipitation (Zhang *et al.* 2013).

We use the number of livestock per ha as a proxy for productivity measure for two reasons. First, the information on the number of livestock over time is easily accessible from the households. To ensure the number of livestock is comparable over time and across households, all animals are converted to sheep by a standard conversion formula.[3] Second, while the income/revenue of livestock production per ha may be a better measure of productivity, we do not have the livestock income/revenue data for previous years. Despite our initial intention to collect the recall data on livestock income for past years, it proved to be extremely difficult to have farmers to recall such information. In the end, we only collected livestock income data for 2017.

One potential problem to use the number of livestock per ha as a proxy for productivity is the nonlinear relationship between herd size and livestock output, that is, output might decline if there were too many livestock on the grassland. To examine whether this will bias our estimates, we performed a couple of robustness checks. In the first robustness check, we restricted the sample to households that raised no more than nine livestock per ha. Nine livestock per ha turned out to be the smallest number in our sample for joint-operated households that graze on the same land together. They basically have an agreement on the amount of livestock that each household can carry. If the number of livestock per ha of those households did not negatively affect the livestock production of other households that jointly operate the grassland, it is reasonable to assume that own production does not decline due to excessive herd size below nine livestock per ha. In the second robustness check, we used the 2017 cross-sectional data on livestock income per ha as the measure of productivity, which yields similar finding.

There is also a potential concern for the fact that data on input variables for previous years are based on respondents' recall. However, we feel that the recall bias in our panel data is not serious for two reasons. First, there is a good record on land allocated to each household by village collective. Land transfers, including those without written contracts, are considered important events by rural households. In fact, respondents' good memory of land information over time is one of the most consistent impressions of our enumerators. Second, as the grazing method in our study area is very

[3] The number of livestock is transformed into sheep units using the following criteria: 1 sheep = 1 sheep unit; 1 lamb = 0.5 sheep unit; 1 goat = 0.9 sheep unit; 1 young goat = 0.4 sheep unit; 1 cattle = 5 sheep unit; and 1 calf = 3.5 sheep unit (Fernández-Giménez *et al.* 2012; Xu 2000; Hu *et al.* 2019).

traditional, herders use very few inputs. Regarding labour, the most important input after land, the activities to be performed in a specific time of a season are very homogenous. In addition, if hired labour is used for livestock production (10–15 per cent in our sample), it involves only a few people in a long-term, which makes recall relatively easy.[4] To systematically test to what extent recall bias affects our panel estimates, we also use 2017 cross-sectional data to explore the IR, and the results are consistent. While this robustness check helps examine the degree to which our estimates are sensitive to the presence of classical measurement errors, we would also like to acknowledge that there may be nonclassical measurement errors in herd size (e.g. due to interhousehold lending) as well as income (e.g. from milk consumed by calves) that we are unable to examine.

Descriptive statistics on household characteristics and livestock production are reported in Table S1.[5] While the land area transferred through the rental market was much smaller than average area of land owned (461 ha) or operated (475 ha), the data point towards improved functioning of the land rental market between 2008 and 2017, both in terms of participation and in terms of area transferred. For example, the share of households who rented in and out land increased from 8 per cent to 23 per cent and from 1 per cent to 2 per cent, respectively.[6] Moreover, for herders who rented in (out) land, the amount of area rented in (out) increased from 8 to 25 ha (from 0.4 to 10 ha). At the same time, the labour market allowed herders to diversify work opportunities considerably, with the share of households supplying labour to the market[7] increasing from 18 per cent in 2008 to 27 per cent from in 2017. However, the IR between livestock number per ha and household operated land size, illustrated in Figure 1, suggests that improvements in the factor markets may not be sufficient for herders to optimise their production scale. This is also supported by the finding that households operating larger grassland used smaller labour input per unit area (Figure 2).[8]

[4] The maximum number of hired labour in our sample is four (by number of people).

[5] Descriptive statistics on plot characteristics and geographic information are reported in Tables S3 and S4. All plots characteristics are weighted by plot area to household operated land size in order to aggregate to the household level. While land size and information on land transaction as well as grass type were collected for all the plots, other land characteristics and GPS coordinates were collected for randomly selected plots in each household. Regarding these 'other land characteristics' and GPS coordinates, 55% of households in our sample have information from all their plots.

[6] Please note that we do not observe the full distribution of rent-out households, as our survey focuses on households that have not exited from livestock production.

[7] They are agricultural workers, manufacturing workers, construction workers, craftsman, mining workers, service workers, vendors and herding labour for other households.

[8] All logarithms are taken hyperbolic sine transformation to define zero values following log $(y + (y^2 + 1)^{1/2})$. To take the transformation, we avoid extremely small labour input per ha by scaling up unit land size to 100 ha.

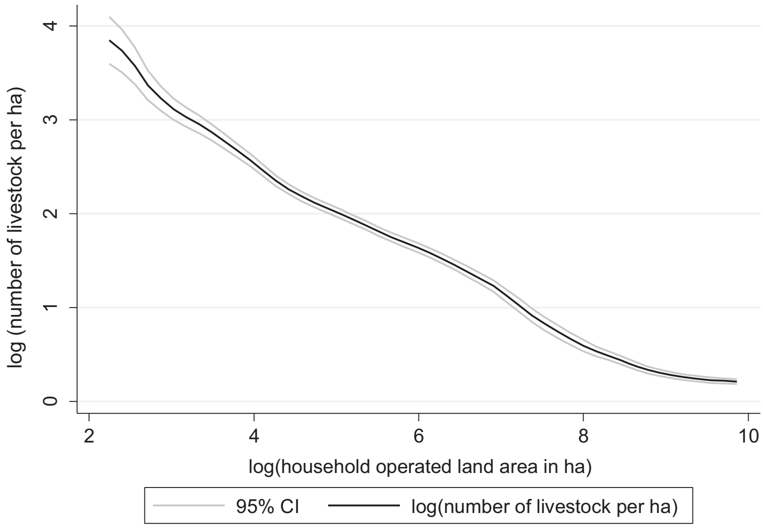

Figure 1 Local polynomial regression of livestock per ha on operated land size.
Note: All livestock are converted to sheep.

3.2 Estimation strategy

To identify factors correlated with the IR, we regressed livestock production per ha on household operated land size and a set of household characteristics:

$$\log Y_{ijt} = \beta_1 \log A_{ijt} + \beta_2 X_{ijt} + \beta_3 G_{jt} + \phi_i + T_t + \varepsilon_{ijt}, \tag{1}$$

where Y_{ijt} is the number of livestock per ha raised by household i in village j in year t. A_{ijt} is household operated land size. X_{ijt} is a vector of household characteristics including (i) livestock characteristics (the shares of full-grown livestock, female livestock for reproduction, and cattle); (ii) land for nongrazing use (an indicator variable for land used for producing forage grass/fodder or cutting grass); (iii) household wealth (per capita consumption of durables goods); (iv) household demographic information (household size as well as the share of household members by age and gender, hukou status, education level and health conditions); and (v) the status in the land rental market (indicator variables for renting in and out some land) and the status in the labour market (indicator variables for hiring labour for grazing and labour supply to the market). G_{jt} is the monthly rainfall. ϕ_i is a vector of household fixed effects that control for time-invariant household characteristics. T_t is a vector of year fixed effects that control for common trends for every household in the same year. ε_{ijt} is the error term clustered by village. β_1 is the parameter of our interest. A negative and statically significant β_1 would suggest the existence of IR between livestock number per ha and household operated land size.

If land characteristics are simultaneously correlated with operated land size and the number of livestock per ha, these omitted characteristics may explain

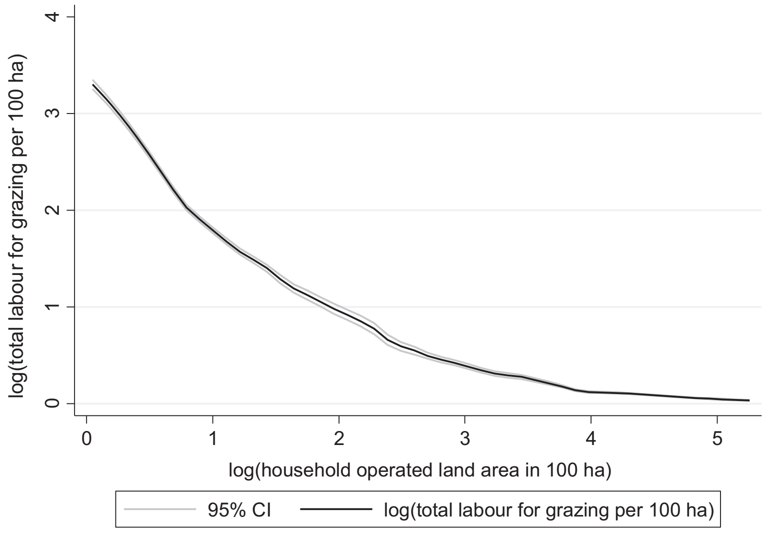

Figure 2 Local polynomial regression of total labour for grazing per 100 ha on operated land size.

the IR and lead to a spurious IR between operated land size and the number of livestock per ha. We, therefore, expanded Equation (1) by controlling for a vector of land characteristics such as grass type, joint operation, practice of rotational grazing, subsidy status, distance from the land to the dwelling, soil type, land slope and land quality. As land characteristics are aggregated using plot-level information, they are weighted by plot size to household operated land size. As the IR ($\beta_1 < 0$) remained to the control of land characteristics, we then further explored the role of inputs and labour in two steps.

First, we added a vector of inputs, including the logarithms of shelter area and expenses per ha, on forage grass and fodder. Next, on the basis of these expansions, we added the total labour for grazing per ha in logarithm. If β_1 becomes less negative or statistically insignificant with the addition of the total labour variable, we say the IR could be largely explained by labour input. In this case, we would replace Y_{ijt} with L_{ijt} (total labour for grazing per 100 ha[9]) in Equation (1), to directly examine whether there is an IR between operated land size and labour input per ha. This IR may be attributed to the imperfections in the land rental market and/or the labour market, which did not allow herders to optimise the ratio of labour to land. To provide evidence, we first test the separation hypothesis following Dillon and Barrett (2017) and Deininger *et al.* (2018):

[9] To take hyperbolic sine transformation to define zero labour following $\log(y_i+(y_i^2 + 1)^{1/2})$, we avoid extremely small labour input per ha by scaling up unit land size to 100 ha. Operated land size and other land size-based variables in the regressions are also scaled up to 100 ha.

$$\log \mathrm{TL}_{ijt} = \gamma_1 \log \mathrm{OA}_{ijt} + \gamma_2 H_{ijt} + \gamma_3 P_{jt} + \gamma_4 G_{jt} + \phi_i + T_t + \varepsilon_{ijt}, \quad (2)$$

where TL_{ijt} is total labour for grazing; OA_{ijt} is household land endowment; H_{ijt} is a vector of household labour endowment including the logarithm of household size, the share of prime male members, the share of elderly male members, and the share of prime female members; P_{jt} is a vector of prices including the wage rage, the land rental rate, and the price of forage grass; and other variables are defined as in Equation (1). We also augment Equation (2) by controlling for (i) the hukou status, the education level and the health condition of household members; and (ii) plot characteristics as described for expanded Equation (1). γ_2 is the vector of parameters of interest. Rejection of $\gamma_2 = 0$ implies the absence of complete and competitive markets.

Our second evidence is from descriptive regressions for market participation denoted by MP_{ijt}, a vector including indicator variables for household renting in land and hiring in labour for grazing.

$$\mathrm{MP}_{ijt} = \delta_1 R_{ijt} + \delta_2 G_{jt} + \phi_i + T_t + \varepsilon_{ijt}. \quad (3)$$

We examine whether the household labour–land endowment ratio (number of adult equivalent household members divided by owned land area) denoted by R_{ijt} can explain the pattern of land rental and labour hiring with and without controlling for household demographic information. δ_1 is the parameter of interest. Rejection of $\delta_1 = 0$ indicates frictions in the market.

If evidence points towards market failure, it is important to understand whether the imperfect markets have the potential to improve allocative efficiency. We augmented Equation (1) by estimating:

$$\log Y_{ijt} = \theta_1 \log A_{ijt} + \theta_2 \log A_{ijt} * \mathrm{MP}_{ijt} + \theta_3 X_{ijt} + \theta_4 G_{jt} + \phi_i + T_t + \varepsilon_{ijt}, \quad (4)$$

While θ_1 captures the IR between livestock number per ha and household operated land size for autarky households, θ_2 measures differences in IR between factor market participants with autarky households.

According to the descriptive statistics in Table S2, market participation increased between 2008 and 2017. If the impact of time trend (for instance, technology advancement) on large-scale grassland is different from that on small-scale grassland, the difference in the IR between market participants and autarky households may be correlated with other factors. Hence, we added a vector of interactions between household operated land size and year dummies to control for time trends by operated land size for a robustness check.

4. Econometric results and discussion

We observed that the IR between operated land size and the number of livestock per ha can be largely explained by labour use intensity, which is also negatively correlated with the operated land size. This is consistent with market failure supported by rejection of the separation hypothesis and the fact that the labour–land endowment ratio explains much of the market activities. The results from regressions with the addition of the interaction of market participation and land size show (i) the labour market did not play any significant role in improving allocative efficiency among herders, as the coefficients on the interaction terms between land size and participation in either side of the labour market were statistically nonsignificant; (ii) compared to autarky households, the rent-in households enjoyed a somewhat smaller IR (but of considerable magnitude); (iii) the rent-out households, on the other hand, enjoyed an IR significantly larger than that of autarkic households. These heterogeneous results are robust to varying time trends by operated land size.

4.1 Labour-explained IR

Table 1 presents the results of the IR for livestock number per ha. The base model result shows that a 1 per cent increase in operated land area reduced the number of livestock per ha by 0.52 per cent (Column 1). Although the inclusion of plot characteristics (Columns 2 and 3) and various inputs (Column 4) explained the IR at most by 0.13 per cent, adding labour dramatically weakened the IR not only in magnitude but also in statistically significance (Column 5). Similar results were observed when we use the restricted sample (Table S5, panel A) or measure productivity with 2017 livestock income per ha (Table S5, panel B). Results in Table 1 suggest that difference in labour use intensity largely explained the IR between productivity and household operated land size; therefore, it was interesting to regress labour use intensity against the operated land size by controlling for other variables, as in Table 1. The results presented in Table 2 suggest that a 1 per cent increase in operated land area reduced total labour use intensity by 0.86–0.93 per cent. Finally, to exclude the possibility that recall bias drives the IR, Table S6 reports results on IR for livestock number per ha (panel A) and total labour per ha (panel B) using 2017 cross-sectional data. The cross-sectional results are largely consistent with the results based on the panel data. Therefore, it shows that our results are not driven by the choice of output measure.

4.2 Evidence on market failure

Households' labour endowment will affect their labour use in the absence of complete and competitive markets. This leads to nonseparation between

Table 1 Regressions of livestock per ha on operated land size

	(1)	(2)	(3)	(4)	(5)
Ln (household operated land area in ha)	−0.523***	−0.564***	−0.456***	−0.396***	−0.189
	(0.124)	(0.127)	(0.127)	(0.132)	(0.162)
Observations	2,081	2,081	2,081	2,081	2,081
R^2	0.942	0.938	0.940	0.941	0.943
Household fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Cumulative rainfall from Apr. to Sep.	Yes	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes	Yes
Plot characteristics	No	Some	All	All	All
Inputs	No	No	No	Yes	Yes
Labour	No	No	No	No	Yes

Notes: ***$P < 0.01$; **$P < 0.05$; *$P < 0.1$. All livestock are converted to sheep. The share of full-grown livestock, the share of female livestock and the share of cattle are controlled for. Household characteristics include an indicator variable for any land using for producing forage grass/fodder or cutting grass, the statuses in the factor markets (i.e. indicator variables for renting in some land, renting out some land, hiring labour for grazing and supplying labour to the labour market), household wealth (i.e. per capita consumption of durable goods), and household size as well as household demographic information (children under age 16 are counted as 0.5 adults). Plot characteristics include grass type, joint operation, practice of rotational grazing, subsidy status, distanced from the plot to the dwelling, soil type, land slope and land quality, as presented in Table S3. All plot characteristics are weighted by plot area to household operated land size. While all plot characteristics were collected for about 55% of the households in the survey, except grass type, other plot characteristics were collected for selected plots in the remaining 45% households. We control for grass type in Column (2). We control for all plot characteristics in Columns (3) to (5) and add indicator variables to indicate whether specific plot characteristics were collected. Inputs are controlled by shelter area and expenses on forage grass and fodder. Labour are controlled by the logarithm of total labour per ha (family labour plus hired labour who working for grazing). Robust standard errors in parentheses are clustered by village.

households' consumption and production decisions. Table 3 presents the results for testing the separation hypothesis. The null hypothesis that all the demographic variables (household size and the shares of different demographic groups) are jointly equal to zero is rejected at the 1 per cent level of significance. Moreover, the estimated elasticity of labour demand with respect to household size ranges from 0.87 in the base model to 0.91 in the expanded model controlling for additional household and plot characteristics, pointing towards herders' dependence on endowment due to the market failure. Consistently, the descriptive regressions of land and labour market participation demonstrate that labour–land endowment ratio explained much of the pattern of land rental and/or labour hiring (Table 4). More specifically, the labour-abundant households were more likely to rent in land (Columns 1 and 2) and land-abundant households were more likely to hire labour for grazing (Columns 3 and 4). Heterogeneity by operated land size reported in Table 5 suggests that market failure affected small households (below median size) more than large households (equal or above median size). While small households' IR for output was 1.17 times that of large households (Columns 1 and 2), their IR for labour doubles that of large households (Columns 3 and 4).

Table 2 Regressions of total labour for grazing per 100 ha on operated land size

	(1)	(2)	(3)	(4)
Ln (household operated land area in 100 ha)	−0.931*** (0.125)	−0.900*** (0.142)	−0.879*** (0.143)	−0.861*** (0.142)
Observations	2,082	2,082	2,082	2,082
R^2	0.984	0.984	0.985	0.985
Household fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Cumulative rainfall from Apr. to Sep.	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes
Plot characteristics	No	Some	All	All
Inputs	No	No	No	Yes

Notes: ***$P < 0.01$; **$P < 0.05$; *$P < 0.1$. The share of full-grown livestock, the share of female livestock, and the share of cattle are controlled for. Household characteristics include an indicator variable for any land using for producing forage grass/fodder or cutting grass, the statuses in the factor markets (i.e. indicator variables for renting in some land, renting out some land, hiring labour for grazing and supplying labour to the labour market), household wealth (i.e. per capita consumption of durable) and household size as well as household demographic information (children under age 16 are counted as 0.5 adults). Plot characteristics include grass type, joint operation, practice of rotational grazing, subsidy status, distanced from the plot to the dwelling, soil type, land slope and land quality, as presented in Table S3. All plots characteristics are weighted by plot area to household operated land size. While all plot characteristics were collected for about 55% of the households in the survey, except grass type, other plot characteristics were collected for selected plots in the remaining 45% households. We control for grass type in Column (2). We control for all plot characteristics in Columns (3) to (5) and add indicator variables to indicate whether specific plot characteristics were collected. Inputs are controlled by shelter area and expenses on forage grass and fodder. Robust standard errors in parentheses are clustered by village.

4.3 The role of factor markets

We have shown significant evidence of land and labour market failure, and the existence of considerable IR between farm size and productivity. It is important to understand whether the market participation status affects IR. Table 6 presents the heterogeneous results of IR by households' status of participating in the factor markets. Results for autarky households were similar to those in Table 1. Adding plot characteristics (Column 1) and various inputs (Column 2) only slightly reduced the magnitude of the IR estimates, without noticeable change to the level of significance. However, the inclusion of labour significantly reduced the magnitude of IR and rendered it statistically nonsignificant (Column 3), suggesting that the difference in labour use is likely to be the main reason for the presence of IR. Interestingly, we observed that the estimated IRs differ considerably between land rental market participants and autarky households. For example, compared to autarky households, renting in land significantly reduced the IR by 0.06 per cent and renting out land significantly increased IR by 0.28–0.3 per cent (Columns 1–2). Although renting in land reduced the magnitude of the IR, the reduction was not large enough to make the IR to disappear as supported by the fact that we failed to reject the null hypothesis that IR does not exist among the rent-in households (i.e. $\theta_1 + \theta_{21} = 0$). The IR is only eliminated when labour input is included as the control variable (Column 3), consistent

Table 3 Testing the separation hypothesis

	(1)	(2)	(3)	(4)
Ln (household-owned area in ha)	0.013 (0.012)	0.024* (0.013)	0.029* (0.016)	0.036 (0.025)
Ln (household size) (γ_{21})	0.870*** (0.081)	0.901*** (0.095)	0.907*** (0.097)	0.910*** (0.102)
Prime male share (γ_{22})	0.166 (0.162)	0.015 (0.170)	0.017 (0.170)	−0.005 (0.168)
Elderly male share (γ_{23})	0.234 (0.156)	0.005 (0.178)	0.008 (0.177)	0.012 (0.181)
Prime female share (γ_{24})	0.069 (0.058)	0.021 (0.059)	0.025 (0.059)	0.026 (0.055)
Observations	2,082	2,082	2,082	2,082
R^2	0.907	0.912	0.913	0.916
F Test $\gamma_{21} = \gamma_{22} = \gamma_{23} = \gamma_{24} = 0$	31.33***	24.85***	24.31***	22.35***
Price of inputs	Yes	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Cumulative rainfall from Apr. to Sep.	Yes	Yes	Yes	Yes
Household demographic information	No	Yes	Yes	Yes
Plot characteristics	No	No	Some	All

Notes: ***$P < 0.01$; **$P < 0.05$; *$P < 0.1$. The dependent variable is total labour for grazing. Wage rate, land rental rate, and the price of forage grass are controlled for throughout. Household demographic information includes the hukou status, the education level and the health condition of household members. Plot characteristics include grass type, joint operation, practice of rotational grazing, subsidy status, distanced from the plot to the dwelling, soil type, land slope, and land quality, as presented in Table S3. All plots characteristics are weighted by plot area to household operated land size. While all plot characteristics were collected for about 55% of the households in the survey, except grass type, other plot characteristics were collected for selected plots in the remaining 45% households. We control for grass type in Column (3). We control for all plot characteristics in Column (4) and add indicator variables to indicate whether specific plot characteristics were collected. Robust standard errors in parentheses are clustered by village.

Table 4 Regressions of market participation

	Rent in some land		Hire labour for grazing	
	(1)	(2)	(3)	(4)
Number of adult equivalent household members/owned land area in ha	0.731* (0.426)	0.695* (0.384)	−0.390*** (0.140)	−0.315** (0.140)
Observations	2,073	2,073	2,073	2,073
R^2	0.708	0.713	0.834	0.835
Household fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Cumulative rainfall from Apr. to Sep.	Yes	Yes	Yes	Yes
Household demographic information	No	Yes	No	Yes

Notes: ***$P < 0.01$; **$P < 0.05$; *$P < 0.1$. The dependent variables are indicator variables for market participation. Household demographic information includes the share of prime male members, the share of elderly male members, the share of prime female members, and the hukou status, the education level and the health condition of household members. Robust standard errors in parentheses are clustered by village.

Table 5 Heterogeneity by land size

	Livestock per ha		Total labour for grazing per 100 ha	
	Operated land size < median (1)	Operated land size ≥ median (2)	Operated land size < median (3)	Operated land size ≥ median (4)
Ln (household operated land area in ha)	−0.547*** (0.147)	−0.467** (0.212)	−1.571*** (0.153)	−0.752*** (0.083)
Observations	1,040	1,041	1,041	1,041
R^2	0.930	0.925	0.971	0.976
Household fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Cumulative rainfall from Apr. to Sep.	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes
Plot characteristics	No	No	No	No
Inputs	No	No	No	No

Notes: ***$P < 0.01$; **$P < 0.05$; *$P < 0.1$. All livestock are converted to sheep. The share of full-grown livestock, the share of female livestock, and the share of cattle are controlled for. Household characteristics include an indicator variable for any land using for producing forage grass/fodder or cutting grass, the statuses in the factor markets (i.e. indicator variables for renting in some land, renting out some land, hiring labour for grazing, and supplying labour to the labour market), household wealth (i.e. per capita consumption of durable goods), and household size as well as household demographic information (children under age 16 are counted as 0.5 adults). Robust standard errors in parentheses are clustered by village.

with the results in Table 1. Thus, this suggests that labour use difference is responsible for the existence of IR. By contrast, the labour market plays a much more limited role in affecting the IR between livestock number per ha and the operated farm size (versus the land rental market), as suggested by the small and nonsignificant estimates of the coefficients of the interaction terms between operated farm size and the labour market participation dummy throughout the regression specifications (Columns 1–3). To examine whether these results are driven by time trends rather than households' participation in the factor markets, we controlled for a vector of interactions between household operated land size and the year dummies in Columns 4–6. The estimates are similar to those in Columns 1–3, suggesting that it is indeed the herders' participation status in the land rental market rather than the time trends that affects the magnitude of the IR.

Finally, we explored the IR between labour use intensity and operated land size to identify the labour-explained IR for factor market participants. Table 7 presents the heterogeneous results by herders' participation status in factor markets. In line with the OLS estimates in Table 2, a 1 per cent increase in operated land area reduced the total labour use per ha for grazing by 1.08–1.09 per cent among autarky households (Columns 1 and 2). This estimate

Table 6 Regressions of livestock per ha on operated land size by factor market status

	(1)	(2)	(3)	(4)	(5)	(6)
Ln (household operated land area in ha) (θ_1)	−0.403***	−0.354**	−0.151	−0.392***	−0.345**	−0.147
	(0.129)	(0.133)	(0.165)	(0.129)	(0.133)	(0.164)
Dummy: Rent in some land × Ln (household operated land area in ha) (θ_{21})	0.064**	0.062**	0.066**	0.076**	0.072**	0.073**
	(0.030)	(0.030)	(0.031)	(0.031)	(0.031)	(0.031)
Dummy: Rent out some land × Ln (household operated land area in ha) (θ_{22})	−0.296***	−0.283***	−0.282***	−0.281***	−0.272***	−0.273***
	(0.074)	(0.074)	(0.073)	(0.075)	(0.075)	(0.074)
Dummy: Hire labour for grazing × Ln (household operated land area in ha) (θ_{23})	−0.007	−0.007	0.000	−0.002	−0.002	0.003
	(0.035)	(0.033)	(0.027)	(0.035)	(0.033)	(0.028)
Dummy: Supply labour to the labour market × Ln (household operated land area in ha) (θ_{24})	−0.028	−0.025	−0.019	−0.028	−0.024	−0.019
	(0.064)	(0.064)	(0.063)	(0.064)	(0.064)	(0.063)
Dummy: Rent in some land	−0.107	−0.116	−0.097	−0.108	−0.116	−0.096
	(0.097)	(0.098)	(0.097)	(0.098)	(0.098)	(0.098)
Dummy: Rent out some land	0.024	0.039	0.024	0.034	0.047	0.030
	(0.144)	(0.139)	(0.139)	(0.145)	(0.140)	(0.140)
Dummy: Hire labour for grazing	−0.000	0.003	−0.080	−0.004	−0.000	−0.083
	(0.117)	(0.103)	(0.081)	(0.116)	(0.103)	(0.080)
Dummy: Supply labour to the labour market	0.053	0.060	0.125	0.053	0.061	0.124
	(0.072)	(0.072)	(0.081)	(0.072)	(0.072)	(0.081)
Observations	2,081	2,081	2,081	2,081	2,081	2,081
R^2	0.947	0.948	0.949	0.947	0.948	0.949
Test $\theta_1 + \theta_{21} = 0$	−0.339**	−0.292**	−0.085	−0.316**	−0.273**	−0.074
Test $\theta_1 + \theta_{22} = 0$	−0.699***	−0.637***	−0.433**	−0.673***	−0.617***	−0.420**
Year-specific Ln (household operated land area in ha)	No	No	No	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Table 6 (*Continued*)

	(1)	(2)	(3)	(4)	(5)	(6)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Cumulative rainfall from Apr. to Sep.	Yes	Yes	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Plot characteristics	All	All	All	All	All	All
Inputs	No	Yes	Yes	No	Yes	Yes
Labour	No	No	Yes	No	No	Yes

Notes: ***$P < 0.01$; **$P < 0.05$; *$P < 0.1$. All livestock are converted to sheep. The share of full-grown livestock, the share of female livestock, and the share of cattle are controlled for. Household characteristics include an indicator variable for any land using for producing forage grass/fodder or cutting grass, the statuses in the factor markets (i.e. indicator variables for renting in some land, renting out some land, hiring labour for grazing, and supplying labour to the labour market), household wealth (i.e. per capita consumption of durable goods), and household size as well as household demographic information (children under age 16 are counted as 0.5 adults). Plot characteristics include grass type, joint operation, practice of rotational grazing, subsidy status, distanced from the plot to the dwelling, soil type, land slope, and land quality, as presented in Table S3. All plots characteristics are weighted by plot area to household operated land size. While all plot characteristics were collected for about 55% of the households in the survey, except grass type, other plot characteristics were collected for selected plots in the remaining 45% households. We control for all plot characteristics, and add indicator variables to indicate whether specific plot characteristics were collected. Inputs are controlled by shelter area and expenses on forage grass and fodder. Labour are controlled by the logarithm of total labour per ha (family labour plus hired labour who working for grazing). Robust standard errors in parentheses are clustered by village.

Table 7 Regressions of total labour for grazing per 100 ha on operated land size by factor market status

	(1)	(2)	(3)	(4)
Ln (household operated land area in 100 ha) (θ_1)	−1.093***	−1.079***	−1.086***	−1.074***
	(0.108)	(0.106)	(0.108)	(0.107)
Dummy: Rent in some land × Ln (household operated land area in100 ha) (θ_{21})	0.171***	0.169***	0.190***	0.188***
	(0.039)	(0.038)	(0.041)	(0.040)
Dummy: Rent out some land × Ln (household operated land area in 100 ha) (θ_{22})	−0.307***	−0.305***	−0.286***	−0.285***
	(0.060)	(0.060)	(0.059)	(0.059)
Dummy: Hire labour for grazing × Ln (household operated land area in 100 ha) (θ_{23})	−0.075**	−0.074**	−0.063**	−0.063**
	(0.029)	(0.029)	(0.029)	(0.028)
Dummy: Supply labour to the labour market × Ln (household operated land area in 100 ha) (θ_{24})	−0.010	−0.011	−0.003	−0.003
	(0.046)	(0.046)	(0.044)	(0.045)
Dummy: Rent in some land	−0.090**	−0.092**	−0.091**	−0.093**
	(0.036)	(0.035)	(0.037)	(0.036)
Dummy: Rent out some land	0.090	0.097	0.100	0.105
	(0.073)	(0.073)	(0.072)	(0.072)
Dummy: Hire labour for grazing	0.227***	0.226***	0.223***	0.222***
	(0.067)	(0.066)	(0.067)	(0.066)
Dummy: Supply labour to the labour market	−0.216***	−0.215***	−0.217***	−0.216***
	(0.051)	(0.049)	(0.051)	(0.049)
Observations	2,082	2,082	2,082	2,082
R^2	0.987	0.987	0.987	0.987
Test $\theta_1 + \theta_{21} = 0$	−0.922***	−0.910***	−0.896***	−0.886***
Test $\theta_1 + \theta_{22} = 0$	−1.400***	−1.384***	−1.372***	−1.359***
Year-specific ln (operated land area in 100 ha)	No	No	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Cumulative rainfall from Apr. to Sep.	Yes	Yes	Yes	Yes
Household characteristics	Yes	Yes	Yes	Yes
Plot characteristics	All	All	All	All
Inputs	No	Yes	No	Yes

Notes: ***$P < 0.01$; **$P < 0.05$; *$P < 0.1$. Household characteristics include an indicator variable for any land using for producing forage grass/fodder or cutting grass, the statuses in the factor markets (i.e. indicator variables for renting in some land, renting out some land, hiring labour for grazing, and supplying labour to the labour market), household wealth (i.e. per capita consumption of durable goods), and household size as well as household demographic information (children under age 16 are counted as 0.5 adults). Plot characteristics include grass type, joint operation, practice of rotational grazing, subsidy status, distanced from the plot to the dwelling, soil type, land slope, and land quality, as presented in Table S3. All plots characteristics are weighted by plot area to household operated land size. While all plot characteristics were collected for about 55% of the households in the survey, except grass type, other plot characteristics were collected for selected plots in the remaining 45% households. We control for all plot characteristics, and add indicator variables to indicate whether specific plot characteristics were collected. Inputs are controlled by shelter area and expenses on forage grass and fodder. Robust standard errors in parentheses are clustered by village.

was robust to the addition of time trends (Columns 3 and 4). However, although the IR was significantly weakened by 0.17–0.19 per cent among the rent-in households, we cannot reject the hypothesis that there is no IR between household operated land size and labour use intensity for grazing (test for $\theta_1 + \theta_{21} = 0$). Moreover, except for renting in land, other market activities either did not change the IR (supplying labour) or increased it (renting out land and hiring labour), reinforcing the high degree of factor market imperfection.

5. Conclusion and policy implications

The debate on the IR between land size and productivity in agricultural production has occupied an important position in the agricultural economic literature for the past century. While the literature has almost exclusively focused on crop production, the IRs between land size and productivity in the livestock sector have been completely neglected. In this article, we are among the first to present evidence for the existence of IRs between land size and productivity in livestock production using panel data from pastoral areas in China. We find that the IRs are mainly explained by differences in labour input use. This is consistent with the classical explanation of market failure, as evidenced by the rejection of the separation hypothesis and the fact that households' labour–land endowment ratio explains much of the factor market activities. These findings suggest that the current factor market conditions prevent herders from optimising their operations and measures to improve the functioning of land rental markets and labour markets are essential for improving the efficiency of pasture-based livestock production. Our results also suggest that beyond crop production factors and the artefact of systematic misreporting of crop output recently documented by the literature in the crop sector, factor market imperfections may remain as one of the important factors to drive IRs, which supports relevant studies in the crop sector.

One limitation of our article is the under representation of rent-out herders in our sample. Therefore, the results provide policy implications for the rent-in side rather than for the rent-out side. While the underrepresentation of rent-out households is not unique to pasture-based livestock production, as numerous existing studies on agricultural land rental participation encounter the serious underrepresentation problem of rent-out households in the study samples (Deininger and Jin 2008; Jin and Jayne 2013). It is important to know why the number of rent-out households is smaller than that of rent-in households. Future surveys should strive to have a balanced sample with representative households from both sides of the rental market.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abay, K.A., Abate, G.T., Barrett, C.B. and Bernard, T. (2019). Correlated non-classical measurement errors, "second best" policy inference, and the inverse size-productivity relationship in agriculture, *Journal of Development Economics* 139, 171–184.

Ali, D. and Deininger, K. (2015). Is there a farm size-productivity relationship in African agriculture? Evidence from Rwanda, *Land Economics* 91, 317–343.

Anderson, K. and Strutt, A. (2014). Food security policy options for China: lessons from other countries, *Food Policy* 49, 50–58.

Assuncao, J.J. and Braido, L.H.B. (2007). Testing household-specific explanations for the inverse productivity relationship, *American Journal of Agricultural Economics* 89, 980–990.

Bardhan, P. (1973). Size, productivity and returns to scale: an analysis of farm-level data in Indian agriculture, *Journal of Political Economy* 81, 1,370–1,386.

Barrett, C.B. (1996). On price risk and the inverse farm size–productivity relationship, *Journal of Development Economics* 51, 193–215.

Barrett, C.B., Sherlund, S.M. and Adesina, A.A. (2008). Shadow wages, allocative inefficiency, and labour supply in smallholder agriculture, *Agricultural Economics* 38, 21–34.

Barrett, C.B., Bellemare, M.F. and Hou, J.Y. (2010). Reconsidering conventional explanations of the inverse productivity-size relationship, *World Development* 38, 88–97.

Benjamin, D. (1992). Household composition, labour markets, and labour demand: testing for separation in agricultural household models, *Econometrica* 60, 287–322.

Benjamin, D. (1995). Can unobserved land quality explain the inverse productivity relationship?, *Journal of Development Economics* 46, 51–84.

Berry, R.A. and Cline, W.R. (1979). *Agrarian Structure and Productivity in Developing Countries*. Johns Hopkins University Press, Baltimore, MD.

Bevis, L. and Barrett, C. (2020). Close to the edge: do behavioral explanations account for the inverse productivity relationship?, *Journal of Development Economics* 143, 1–15.

Bhalla, S.S. and Roy, P. (1988). Misspecification in farm productivity analysis: the role of land quality, *Oxford Economic Papers* 40, 55–73.

Carletto, C., Savastano, S. and Zezza, A. (2013). Fact or artifact: the impact of measurement errors on the farm size–productivity relationship, *Journal of Development Economics* 103, 254–261.

Carletto, C., Gourlay, S. and Winters, P. (2015). From guesstimates to GPStimates: land area measurement and implications for agricultural analysis, *Journal of African Economics* 24, 593–628.

Chayanov, A.V. (1926). *AV Chayanov on the Theory of Peasant Economy*. Manchester University Press, Manchester, UK.

Collier, P. (1983). Malfunctioning of African rural factor markets: theory and a Kenyan example, *Oxford Bulletin of Economics and Statistics* 45, 141–172.

Collier, P. and Dercon, S. (2014). African agriculture in 50 years: smallholders in a rapidly changing world?, *World Development* 63, 92–101.

Deininger, K. and Jin, S. (2008). Land sales and rental markets in transition: evidence from rural Vietnam, *Oxford Bulletin of Economics and Statistics* 70, 67–101.

Deininger, K., Jin, S., Liu, Y. and Singh, S.K. (2018). Can labour-market imperfections explains changes in the inverse farm size-productivity relationship? Longitudinal evidence from rural India, *Land Economics* 94, 239–258.

Desiere, S. and Jolliffe, D. (2018). Land productivity and plot size: is measurement error driving the inverse relationship?, *Journal of Development Economics* 130, 84–98.

Dillon, B. and Barrett, C. (2017). Agricultural factor markets in Sub-Saharan Africa: an updated view with formal tests for market failure, *Food Policy* 67, 64–77.

Eswaran, M. and Kotwal, A. (1986). Access to capital and agrarian production organisation, *Economic Journal* 96, 482–498.

Feder, G. (1985). The relation between farm size and farm productivity: the role of family labour, supervision and credit constraints, *Journal of Development Economics* 18, 297–313.

Fernández-Giménez, M.E., Batkhishig, B. and Batbuyan, B. (2012). Cross-boundary and cross-level dynamics increase vulnerability to severe winter disasters (dzud) in Mongolia, *Global Environmental Change* 22, 836–851.

Fukase, E. and Martin, W. (2016). Who will feed China in the 21st century? Income growth and food demand and supply in China, *Journal of Agricultural Economics* 67, 3–23.

Gourlay, S., Talip, K. and Lobell, D. (2019). A new spin on an old debate: errors in farmer-reported production and their implications for inverse scale – productivity relationship in Uganda, *Journal of Development Economics* 141, 3–35.

Harris, R.B. (2010). Rangeland degradation on the Qinghai-Tibetan plateau: a review of the evidence of its magnitude and causes, *Journal of Arid Environments* 74, 1–12.

Hu, Y., Huang, J. and Hou, L. (2019). Impacts of the grassland ecological compensation policy on household livestock production in China: an empirical study in inner Mongolia, *Ecological Economics* 161, 248–256.

Jin, S. and Jayne, T.S. (2013). Land rental market in Kenya: implications for efficiency, equity, *Household Income and Poverty* 89, 246–271.

Lamb, R.L. (2003). Inverse productivity: land quality, labour markets, and measurement error, *Journal of Development Economics* 71, 71–95.

Muyanga, M. and Jayne, T.S. (2019). Revisiting the farm size–productivity relationship based on a relatively wide range of farm sizes: evidence from Kenya, *American Journal of Agricultural Economics* 101, 1,140–1,163.

National Bureau of Statistics of China (2013). *China Statistical Yearbook 2017*. China Statistics Press, Beijing, China.

National Bureau of Statistics of China (2017). *China Statistical Yearbook 2017*. China Statistics Press, Beijing, China.

OECD and FAO (2013). *OECD-FAO Agricultural Outlook 2013–2022*. OECD Publishing, Paris, France.

Pingali, P. (2007). Westernization of Asian diets and the transformation of food systems: implications for research and policy, *Food Policy* 32, 281–298.

Rae, A.N. and Zhang, X. (2009). China's booming livestock industry: household income, specialization, and exit, *Agricultural Economics* 40, 603–616.

Rae, A.N., Ma, H., Huang, J. and Rozelle, S. (2006). Livestock in China: commodity-specific total factor productivity decomposition using new panel data, *American Journal of Agricultural Economics* 88, 680–695.

Rask, K. and Rask, N. (2011). Economic development and food production-consumption balance: a growing global challenge, *Food Policy* 36, 186–196.

Sen, A.K. (1962). An aspect of Indian agriculture, *Economic Weekly* 14, 243–246.

Thornton, P.E., Running, S.W. and White, M.A. (1997). Generating surfaces of daily meteorological variables over large regions of complex terrain, *Journal of Hydrology* 190, 214–251.

Waldron, S., Brown, C. and Longworth, J. (2010). A critique of high-value supply chains as a means of modernising agriculture in China: the case of the beef industry, *Food Policy* 35, 479–487.

Xu, P. (2000). *Grassland Resources Investigation and Planning*. China Agriculture Press, Beijing, China.

Zhang, T., Huang, Y. and Yang, X. (2013). Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice, *Global Change Biology* 19, 563–570.

Supporting Information

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

Table S1 Descriptive statistics on household characteristics and production.

Table S2 Mean of household characteristics and production by year.

Table S3 Descriptive statistics on plot characteristics and geographic information.

Table S4 Mean of plot characteristics and geographic information by year.

Table S5 Robustness check for using the number of livestock per ha to measure productivity.

Table S6 Robustness check for recall bias using 2017 cross-sectional data.