China Economic Review 77 (2023) 101909

Contents lists available at ScienceDirect

China Economic Review

journal homepage: www.elsevier.com/locate/chieco

Interdependent investments in attached and movable assets under insecure land rights

Meilin Ma [*,1]

Department of Agricultural Economics, Purdue University, USA

ARTICLE INFO

JEL classification:
O12
O16
Q12
Q15

Keywords:
Attached and movable assets
Farm investment
Investment efficiency
Land rights
Large-scale farms

ABSTRACT

The literature concludes that insecure land rights cause farms to make suboptimal capital investment in attached assets, but not in movable assets, implicitly assuming attached and movable assets to be independent. However, the two asset types can be interdependent because the operational efficiency of movable assets, such as farm machinery, typically depends on field conditions, such as land fragmentation. Thus, investment in attached assets may affect investment in movable assets via farm infrastructure. I develop a conceptual model to explain why tenure insecurity may lead a farm to under-invest in attached assets and over-invest in low-efficiency movable assets relative to the secure-land-right scenario. To quantify the economic significance of investment inefficiency, I collect unique survey data on large-scale farms, for which machinery is of particular importance in production, in Southwest China where land tenure remained insecure in 2016. Simulations based on the large-farm survey data suggest that the suboptimal investment occurs given fairly small probabilities of losing some farmland and results in considerable economic losses. The findings have important policy implications regarding land reforms and farm infrastructure in developing economies.

1. Introduction

Enhancing property rights in farmland has long been considered central to increasing agricultural productivity and the long-term economic growth of developing economies (North & Thomas, 1973). Insecure land rights lead to an inefficient allocation of resources. For example, insecure land tenure causes suboptimal allocation of household labor (de Janvry, Emerick, Gonzalez-Navarro, & Sadoulet, 2015) and impedes the efficient allocation of farmland (Deininger, Jin, & Ma, 2022).

Capital allocation within farms depends on the rights over expected returns to investments and, thus, also depends on the nature of land rights (Besley, 1995; Goldstein & Udry, 2008; Fenske, 2011). In the economic literature, capital investment is typically classified into two types. The first type is investment in movable (i.e., non-sunk) assets that can be moved at a trivial cost and used in different locations. Tractors, harvesters, and livestock are examples. The other is investment in assets that are attached to the land (i.e., sunk assets), meaning that the assets cannot be moved without incurring substantial costs or would become useless once relocated. Trees, roads, and pipelines are examples. Except that the two types of investment may compete for a fixed budget (Carter & Olinto, 2003), they are assumed to be independent in existing theoretical models. The general and intuitive conclusion is that insecure land rights only affect the investment in attached assets.

* Corresponding author.
E-mail address: mameilin@purdue.edu.
[1] Krannert Building, 403 W. State Street, West Lafayette, IN, USA.

https://doi.org/10.1016/j.chieco.2022.101909
Received 8 July 2022; Received in revised form 21 October 2022; Accepted 16 December 2022
Available online 19 December 2022
1043-951X/

Depending on the context, the assumption of independent attached and movable investments may or may not be appropriate. For example, while a smallholder is likely to take farm infrastructure (a major form of attached assets) as given, a large farm, which may rely heavily on mechanical power in production, can invest in its own fields to facilitate the use of certain machines, because infrastructure is a key complementary input for mechanization (Jat, Gupta, Saharawat, & Khosla, 2011; Deininger, Monchuk, Nagarajan, & Singh, 2017; Wang, Yamauchi, Huang, & Rozelle, 2020). Logically, if insecure land tenure distorts the investment in attached assets, it can also lead to suboptimal investment in movable assets.

Considering the potential interdependence between investments in attached and movable assets, it is natural to ask to what extent the insecure land rights affects both types of farm investment, and what the magnitude of efficiency loss is caused by the suboptimal allocation of capital. In this article, I build a novel model to address two questions regarding relatively large farms facing insecure land rights: 1) how are investment decisions in attached and movable assets affected by insecure land rights, when the two types of investment are interdependent, and 2) what is the magnitude of efficiency loss due to suboptimal investments?

After reviewing the literature on farm investment in Section 2, I develop the conceptual model in Section 3. To characterize investment returns from attached and movable assets under insecure land rights, a two-period real-option model is built. In the model, the efficiency of movable assets depends on the quality of farm infrastructure. The farm chooses between two investment options: investing in farm infrastructure and using high-efficiency movable assets, or not investing in infrastructure and using low-efficiency movable assets. I show that the farm investment tends to be suboptimal under insecure land rights – under-investing in attached assets and over-investing in low-efficiency movable assets – compared with the investment under secure land rights.

To quantify the efficiency loss due to suboptimal investment decisions, I calibrate the model by employing primary 2016 survey data of large farms in a southwestern province of China. These farms provide an appropriate economic setting for calibrating the model because of two main reasons. First, large farms in China suffer from nontrivial insecurity in land rights due to land reallocation and expropriation by local governments during the period surveyed (Ma, 2022). Second, infrastructure of the farmland is typically too poor to support high-efficiency machinery (Fei et al., 2016) and public investment is limited (Meng & Zhang, 2011), making private investment in infrastructure particularly important for large farms. I employ actual operational parameters of grain harvesters to measure the efficiency difference between low- and high-efficiency machines. Harvesters are chosen as the example, because they are widely used by large grain farms in China and have operational parameters available to researchers.

Simulation outcomes in Section 4 suggest that, though large farms tend to find investing in infrastructure and high-efficiency machinery optimal under secure land rights, they may switch to investing in low-efficiency machinery given a relatively small probability of losing some leased land. Potential net production value of farms may be 10–40% higher if insecurity in land rights were eliminated. The increase in net production value would be even larger if the high-efficiency machinery is cheaper or more efficient, the required investment in improving infrastructure is lower, the land size is larger, or farm wages are lower.

The contribution of this article is twofold. First, it provides an improved theoretical framework for studying farm investment in attached and movable assets under insecure land rights. It is the first to consider the interdependence between investments in the two types of assets, which is typically overlooked but critical for many developing regions with poor farm infrastructure and insufficient public investment (Bardhan, Mookherjee, & Kumar, 2012; Deininger et al., 2017). Second, it uses a calibrated model to quantify the efficiency loss due to suboptimal investment and the sensitivity of farm investment to insecurity in land tenure. Outcomes confirm the economic importance of considering the interdependence between the two types of investment. The survey data are also valuable, because detailed data of large farms in developing economies are scant to non-existent, despite an increasingly important role of those farms in Asia and Africa (Zeng & Liu, 2014; Deininger et al., 2022; Foster & Rosenzweig, 2022; Jayne, Wineman, Chamberlin, Muyanga, & Yeboah, 2022).

The findings highlight another source of efficiency gains from eliminating insecurity in land tenure, the efficiency improvement of large-farm investments in movable assets. Besides growing adoption of planters and harvesters on large farms (Yamauchi, 2016), new trends of precision farming and increasing requirements on quality control imply rising investment in advanced movable assets like wireless sensors and unmanned aerial vehicles that rely critically on farm infrastructure. By reducing tenure insecurity, large farms can invest more in infrastructure and high-efficiency machinery, be more productive, and obtain more land from smallholders, creating a virtuous cycle of investment, productivity, and land consolidation. The virtuous cycle pushes the transformation from smallholder farming to a commercialized farming system, along with the tranformation of agri-food supply chains (Barrett, Reardon, Swinnen, & Zilberman, 2022). Though public investments could help reduce investment inefficiency due to insecure land rights, I argue in Section 5 that the state-led investment in farm infrastructure alone may not be effective, sustainable, or efficient, given many unsuccessful land consolidation programs in developing countries (Deininger et al., 2017). Land reforms still seem critical.

2. Farm investment under insecure land tenure

Insecure property rights is a common issue in developing economies and affects investment through multiple channels. First, uncertainty in property rights, or an expropriation risk over the property, acts as a random tax over returns to capital investment and reduces the equilibrium-level investment (Mendelsohn, 1994) or postpones the investment if waiting mitigates the risk (Dixit & Pindyck, 1994). Second, insecurity in property rights reduces investment by limiting the access to credit; for instance, insecure rights prevent land from being used as the collateral (Feder & Onchan, 1987). Third, Besley (1995) argues that insecure rights may leave investors unable to capture potential gains from trading the property, discouraging investment.

Regarding developing economies where insecurity in land tenure is common, many researchers have studied the effects of insecure land rights on farm investment in attached and movable assets. There is an extensive discussion over how insecure land tenure affects farmers' investment in the two types of assets differently. If the insecurity in property rights is taken as given and credit constraints are not binding, theoretical and empirical evidence suggests that insecure tenure only tends to reduce the investment in attached assets, but not movable assets (Jacoby, Li, & Rozelle, 2002; Deininger & Jin, 2006; Deininger, Ali, & Alemu, 2011; Fenske, 2011; Bambio & Bouayad Agha, 2018).

The intuition is straightforward. Because movable assets preserve their value regardless of the location, insecurity in land tenure or uncertainty in the use rights of specific plots ought to be irrelevant. In contrast, returns to the investment in attached assets are obtained only if the same plots are used by the investor for a sufficiently long period of time. All prior models consider investments in attached and movable assets to be independent, except when the two types of investment compete for a fixed budget (Carter & Olinto, 2003). Even under credit constraints, productivities of the two types of assets are not considered to be interdependent.[2]

For smallholder farms, an important form of attached assets, farm infrastructure, is typically treated as exogenously provided by the region- or country-level government (Binswanger, Khandker, & Rosenzweig, 1993; Zhang & Fan, 2004; Wang et al., 2020; Akber & Paltasingh, 2019). This generally seems a reasonable assumption, because the government is a major provider of farm infrastructure in many developing economies, and smallholder farms are too small in scale to make profitable investments in infrastructure (Feder & Feeny, 1991; Deininger & Xia, 2016).

Yet even smallholders invest in infrastructure, such as tubewells and dugwells for irrigation, when tenure security or credit access is enhanced or subsidies are available (Bardhan et al., 2012; Kafle, Omotilewa, Leh, & Schmitter, 2022). The incentive to invest in farm infrastructure is likely to be stronger for large farms, because the interdependence between investments in attached and movable assets tends to be tighter. Relying heavily on mechanical power instead of labor (Sheng, Ding, & Huang, 2019), large farms need high-quality infrastructure to serve as a key complementary input for high-efficiency machinery and other production facilities (Sunding & Zilberman, 2001). For instance, leveled land is an important condition for achieving high efficiency of agricultural production machinery (Jat et al., 2011). Large-sized machinery can only drive on sufficiently wide and paved roads to reach fields (Zeng & Liu, 2014) and need to be operated on sufficiently large, contiguous, regularly-shaped, and leveled plots (Deininger et al., 2017; Wang et al., 2020).

High-quality roads around farmland and high-quality plots are exactly what is lacking in many developing economies in Asia and Africa (Blarel, Hazell, Place, & Quiggin, 1992; Long, 2014). Land fragmentation, for example, is a common problem (Ali, Deininger, & Ronchi, 2019). Though it might serve as a diversification tool to reduce smallholders' exposure to price and yield risks, long distances between plots significantly increase the time needed for setting up and using farming equipment and for managing hired labor. Particularly relevant to this article, fragmentation and disconnection of plots may also make mechanization impossible or much less efficient (Foster & Rosenzweig, 2010).

For large farms in many developing economies, private investment in enhancing the quality of fields is particularly important, because public investment in farm infrastructure is insufficient and declining (Deininger & Xia, 2016). As detailed in online appendix A, I show econometrics evidence that private investment in improving the quality of fields, including merging and leveling plots, improves the productivity of farm machinery based on data of large farms in China.

3. A model of attached and movable investment under insecure land rights

This real-option model characterizes large-farm investment in attached and movable assets under insecure land rights. The central tradeoff for the large farm is between investing in farm infrastructure and using high-efficiency movable assets versus not investing in infrastructure and using low-efficiency movable assets. Core assumptions and insights apply widely to farms in developing economies. As long as a farm is faced with insecure land rights and the field quality is unable to support high-efficiency movable assets like machinery, the model offers a relevant theoretical framework for analyzing farm investment.

3.1. Baseline model

Consider a two-period game for a large farm. The farm is a price-taker in input and output markets and has bought or leased s units of land. The farm intends to cultivate s units of land for two periods, knowing that there is insecurity in land rights. To better align with the empirical context, I consider leased land hereafter, and considering purchased land makes no theoretical diference. Period 1 is free from risk of losing leased land, while some leased land may not be sustained in period 2. The farm decides how much capital to invest in attached assets (i_A) and movable assets (i_M) upon the start of period 1 and chooses how much labor to hire in each period, maximizing the expected net production value over two periods.[3] In this model, attached assets refer to farm infrastructure, and movable assets refer to machinery. Infrastructure determines the choice of machinery, while the machinery chosen determines the production technology and efficiency of hired farm labor.

For simplicity, I assume that there are only two types of movable assets, high-efficiency (H-type) and low-efficiency (L-type) machinery that the large farm may employ. This assumption emphasizes that the enhanced farm infrastructure increases efficiency of machinery mainly by allowing for the use of high-efficiency machines, not by increasing the efficiency of machines on the margin; for

[2] Tenure security can be endogenous to investment in attached assets. For example, Feder, Lau, Lin, and Luo (1992) find that a rural household in China builds a house to establish use rights of the land where the house stands, leading to over-investment in attached assets. Robinson (2005) introduces a theoretical model, which rationalizes both under-investment and over-investment in land, when the security of property rights is endogenous.

[3] Relatively large farms typically rely on hire farm labor for production instead of family labor (Jayne et al., 2022), which is a key distinction from smallholder farms.

instance, better infrastructure leads to higher fuel efficiency of a given machine. Considering higher fuel efficiency of the H-type machinery would not change hypotheses derived from the model.

The H-type machinery has relatively high efficiency in the sense that, for the same operation costs and labor input, it achieves higher production than the L-type does. The H-type machinery can only work on leveled and contiguous plots, while the L-type can work on any plots. The market price of H-type machinery is c_H and that of the L-type machinery is c_L with $c_H > c_L > 0$. The value of both types of machinery is assumed to depreciate to zero by the end of period 2.

Plots are initially fragmented, unleveled, and disconnected, which is exogenous to the large farm. To enhance the quality of fields, the farm must invest in land leveling, merging, and reshaping. Enhancing the infrastructure on each unit of land to facilitate the H-type machinery costs c_f. Ignoring credit constraints, the farm is able to invest in either type of machinery and farm infrastructure. Adding credit constraints is discussed in Section 3.2.

The farm production function is $f(el, s|A)$, where A is the given technological efficiency, s is the size of leased land, and l is the amount of farm labor. The function is twice differentiable, strictly increasing, and concave in both inputs. The efficiency of farm labor, e, depends on the type of machinery employed and is normalized to one ($e_L = 1$) if the L-type machinery is used. When using the H-type machinery, labor efficiency increases to $e_H > 1$, meaning that high-efficiency machinery has a *factor augmentation effect* which is widely used in modeling efficiency-enhancing technologies (e.g., Moschini & Lapan, 1997). The price of farm outputs is normalized to 1.0, while the market wage rate for farm workers is w.

Assume that the initial farm size, s, is large enough to facilitate the use of either H- or L-type machinery provided with appropriate infrastructure. The second period involves a probability ρ_1 of losing land rights for a small number, $\Delta_1 s \in \left(0, \underset{-}{s}\right)$, of units and a probability ρ_2 of losing the land rights for a relatively large number, $\Delta_2 s \in \left[\underset{-}{s}, s\right)$, of units. Losing a portion of leased land causes land fragmentation, disconnection, and unevenness, which may prevent the use of machinery that has strict requirements on land quality.[4]

There are three investment options to consider. Option 1 is not investing in machinery nor infrastructure (i.e., $i_A = i_M = 0$) and purchasing mechanical services at a price of m per unit of land. Agricultural producers, especially smallholders, buy custom services for tillage, planting, and harvesting in many developing economies where the L-type machinery is used by professional operators (Zhang, Yang, & Thomas, 2017).[5]

I denote hired farm labor in period 1 and period 2 without losing land, l_N, and in the two other scenarios of period 2, depending on the realization of risks, l_N' and l_N'', respectively. The probability of not losing land rights in period 2 is $(1 - \rho_1 - \rho_2)$. Losing either a small portion (Δ_1) or a large portion (Δ_2) does not affect the use of L-type machinery services. Denote F as the exogenously determined cost of fixed inputs of cultivating a unit of land, including the land rental. Without losing core insights, I set the time discount factor to one. The objective function for option 1 is:

$$\max_{l_N, l_N', l_N''} E(\pi_N) = Af(l_N|s) - wl_N - (F+m)s \tag{1}$$

$$+(1-\rho_1-\rho_2)[Af(l_N|s) - wl_N - (F+m)s]$$

$$+\rho_1\left[Af\left(l_N'|(1-\Delta_1)s\right) - wl_N' - (F+m)(1-\Delta_1)s\right]$$

$$+\rho_2\left[Af\left(l_N''|(1-\Delta_2)s\right) - wl_N'' - (F+m)(1-\Delta_2)s\right].$$

Option 2 is to invest in the L-type machinery but not in infrastructure (i.e., $i_A = 0$ and $i_M = c_L$). For simplicity, scale the cost of using one's own machinery to zero, so that m in eq. (1) is effectively the price of custom services minus the cost of self-operating H- or L-type machinery which is mainly the cost of fuel. Again, l_L, l_L', and l_L'' denote labor inputs in periods 1 and two land-losing scenarios in period 2, respectively. The objective function for option 2 is expressed in eq. (2):

$$\max_{l_L, l_L', l_L''} E(\pi_L) = Af(l_L|s) - wl_L - Fs - c_L \tag{2}$$

$$+(1-\rho_1-\rho_2)[Af(l_L|s) - wl_L - Fs]$$

$$+\rho_1\left[Af\left(l_L'|(1-\Delta_1)s\right) - wl_L' - F(1-\Delta_1)s\right]$$

$$+\rho_2\left[Af\left(l_L''|(1-\Delta_2)s\right) - wl_L'' - F(1-\Delta_2)s\right].$$

[4] The risk is assumed to be exogenous to farm investment. This is a reasonable assumption, because the risk in land rights in many developing economies is caused by land reallocation or expropriation by local governments or income shocks on lessors (Ma, 2022). Such risks could not be easily reduced by a large farm's capital investment. I discuss this assumption in Section 3.2. Furthermore, one could consider a continuous distribution of $\Delta \in [0,1]$ that represents different portions of land loss. The expected profits would then be written using integrals. Central tradeoffs in the model stay unchanged. I hence choose to stay with a relatively simple characterization of risks in land rights.

[5] Professional machinery operators run the L-type machinery to adapt to various land conditions and maximize the scale of services as they travel across regions and seasons.

Option 3 is to enhance the quality of farmland and purchase the H-type machinery (i.e., $i_A = c_f s$ and $i_M = c_H$). Again, though the unit cost of operating the H-type machinery is likely to be lower than that of operating the L-type machinery, the cost difference is not explicitly incorporated in the model, so that their difference in labor efficiency is highlighted.

The H-type machinery cannot be used due to land fragmentation and unevenness if a relatively large portion of land is lost in the second period (i.e., losing $\Delta_2 s$). This is the most straightforward specification that captures the essential impact of insecure land rights: benefits of investing in infrastructure and the H-type machinery are not fully captured by the farm due to insecure land rights.

If $\Delta_2 s$ is lost, the farm has to retire the H-type machinery at a salvage value of kc_H. If the value of machinery completely and linearly depreciates by the end of period 2, the remaining value by the end of period 1 is $\frac{1}{2}c_H$. I let k fall in $\left(0, \frac{1}{2}\right]$, meaning that the salvage value must not exceed this remaining value on a resale market of used machinery. After selling the H-type machinery, the farm relies on mechanical services. The corresponding objective function for option 3 is:

$$\max_{l_H, l_H^{'}, l_H^{''}} E(\pi_H) = Af(e_H l_H|s) - wl_H - Fs - \left(c_H + c_f s\right) \tag{3}$$

$$+(1-\rho_1-\rho_2)[Af(e_H l_H|s) - wl_H - Fs]$$

$$+\rho_1\left[Af\left(e_H l_H^{'}|(1-\Delta_1)s\right) - wl_H^{'} - F(1-\Delta_1)s\right]$$

$$+\rho_2\left[Af\left(l_H^{\prime\prime}|(1-\Delta_2)s\right) - wl_H^{\prime\prime} - (F+m)(1-\Delta_2)s + kc_H\right].$$

To obtain analytical solutions, specify $f(el, s|A)$ as a Cobb-Douglas function with constant returns to scale: $f(el, s) = As^{\alpha}(el)^{1-\alpha}$ with $\alpha \in (0,1)$. Given the area of land, S, the optimal labor inputs solved in the period is:

$$l^* = \left[\frac{A(1-\alpha)}{w}\right]^{\frac{1}{\alpha}} e^{\frac{1-\alpha}{\alpha}} S.$$

The maximized net production values under the three options are expressed below with $\mu = \alpha\left(\frac{1-\alpha}{w}\right)^{\frac{1-\alpha}{\alpha}} > 0$ and $e_H = \gamma^{\frac{1}{1-\alpha}}$ $(\gamma > 1)$.

$$E(\pi_N)^* = (2-\rho_1-\rho_2)\left[\mu A^{\frac{1}{\alpha}} - (F+m)\right]s + \sum_{i=1}^{2}\rho_i\left[\mu A^{\frac{1}{\alpha}} - (F+m)\right](1-\Delta_i)s;$$

$$E(\pi_L)^* = (2-\rho_1-\rho_2)\left(\mu A^{\frac{1}{\alpha}} - F\right)s + \sum_{i=1}^{2}\rho_i\left(\mu A^{\frac{1}{\alpha}} - F\right)(1-\Delta_i)s - c_L;$$

$$E(\pi_H)^* = (2-\rho_1-\rho_2)\left(\mu A^{\frac{1}{\alpha}}\gamma^{\frac{1}{\alpha}} - F\right)s + \rho_1\left(\mu A^{\frac{1}{\alpha}}\gamma^{\frac{1}{\alpha}} - F\right)(1-\Delta_1)s + \rho_2\left[\mu A^{\frac{1}{\alpha}} - (F+m)\right](1-\Delta_2)s - \left(c_H + c_f s - \rho_2 kc_H\right).$$

To decide which investment option is the best, the farm simply compares these three pairs of maximized farm incomes. Note that the fixed cost, F, is cancelled out in all comparisons.

$$E(\pi_{LN}) \equiv E(\pi_L)^* - E(\pi_N)^* = \left(2 - \sum_{i=1}^{2}\Delta_i\rho_i\right)ms - c_L;$$

$$E(\pi_{HN}) \equiv E(\pi_H)^* - E(\pi_N)^* = (2-\Delta_1\rho_1-\rho_2)\left[\left(\gamma^{\frac{1}{\alpha}} - 1\right)\mu A^{\frac{1}{\alpha}} + m\right]s - \left(c_H + c_f s - \rho kc_H\right);$$

$$E(\pi_{HL}) \equiv E(\pi_H)^* - E(\pi_L)^* = (2-\Delta_1\rho_1-\rho_2)\left(\gamma^{\frac{1}{\alpha}} - 1\right)\mu A^{\frac{1}{\alpha}}s - (1-\Delta_2)\rho_2 ms - \left(c_H - \rho_2 kc_H + c_f s\right) + c_L.$$

The choice of interest is between options 2 and 3, when $E(\pi_{LN}) \geq 0$ and $E(\pi_{HN}) \geq 0$. I show in the next section that $E(\pi_{LN}) \geq 0$ and $E(\pi_{HN}) \geq 0$ align with my survey data. For option 3 to be optimal, $E(\pi_{HL})$ must be positive.

Comparative statics of $E(\pi_{HL})$ follow easily and make intuitive sense. They suggest that the cheaper and more efficient the H-type machinery, and the lower price of mechanical services and farm wage rates, the more that $E(\pi_{HL})$ tends to be positive and that the farm tends to invest in H-type machinery. Interesting to notice that $E(\pi_{HL})$ decreases in the wage rate. The intuition is not complex. The farm hires more labor to operate the H-type machinery compared with the L-type equilibrium. When the wage rate is relatively low, the difference in the amount of hired labor under the two equilibria is relatively large. Given the price of farm outputs, more outputs are made at lower labor costs, enlarging the advantage in labor productivity of option 3. Each of the comparative static could be empirically tested if data are available.

$$\frac{\partial E(\pi_{HL})}{\partial A} > 0, \frac{\partial E(\pi_{HL})}{\partial k} > 0, \frac{\partial E(\pi_{HL})}{\partial c_L} > 0, \frac{\partial E(\pi_{HL})}{\partial c_H} < 0,$$

$$\frac{\partial E(\pi_{HL})}{\partial c_f} < 0, \frac{\partial E(\pi_{HL})}{\partial \gamma} > 0, \frac{\partial E(\pi_{HL})}{\partial m} < 0, \frac{\partial E(\pi_{HL})}{\partial w} < 0.$$

Note that $\frac{\partial E(\pi_{HL})}{\partial s} = (2-\Delta_1\rho_1-\rho_2)\left(\gamma^{\frac{1}{\alpha}}-1\right)\mu A^{\frac{1}{\alpha}} - (1-\Delta_2)\rho_2 m - c_f$ has an ambiguous sign. The sign is ambiguous because a large farm enjoys more efficiency gains from using the H-type machinery on more land, but has to invest more in improving the land infrastructure. Given that I focus on settings where $E(\pi_{HN}) \geq 0$, it follows that:

$$(2-\Delta_1\rho_1-\rho_2)\left[\left(\gamma^{\frac{1}{\alpha}}-1\right)\mu A^{\frac{1}{\alpha}}+m\right]s \geq \left(c_H + c_f s - \rho_2 k c_H\right). \tag{4}$$

Dividing both sides of inequality (4) by s and rearranging terms gives:

$$(2-\Delta_1\rho_1-\rho_2)\left(\gamma^{\frac{1}{\alpha}}-1\right)\mu A^{\frac{1}{\alpha}} \geq c_f + \left[\frac{c_H-\rho_2 k c_H}{s} - (2-\Delta_1\rho_1-\rho_2)m\right]$$

which implies:

$$\frac{\partial E(\pi_{HL})}{\partial s} \geq c_f + \left[\frac{c_H-\rho_2 k c_H}{s} - (2-\Delta_1\rho_1-\rho_2)m\right] - (1-\Delta_2)\rho_2 m - c_f \tag{5}$$

$$\geq \frac{c_H-\rho_2 k c_H}{s} - \left(2-\sum_{i=1}^{2}\Delta_i\rho_i\right)m.$$

Because $0 < k \leq \frac{1}{2}$, the right-hand-side of inequality (5) is larger than $\frac{(1-\frac{\rho_2}{2})c_H}{s} - \left(2-\sum_{i=1}^{2}\Delta_i\rho_i\right)m$.

If the cost of H-type machinery is sufficiently higher than the total cost of custom services on s units of land or $c_H \geq \frac{\left(2-\sum_{i=1}^{2}\Delta_i\rho_i\right)ms}{1-\frac{\rho_2}{2}}$, then $\frac{\partial E(\pi_{HL})}{\partial s} > 0$, suggesting that option 3 is more likely to be optimal as the farm size increases, and vice versa. Because $0 < \rho_i < 1$, it follows that $\frac{\left(2-\sum_{i=1}^{2}\Delta_i\rho_i\right)ms}{1-\frac{\rho_2}{2}} \in (2ms, 4ms)$, the condition $c_H \geq \frac{\left(2-\sum_{i=1}^{2}\Delta_i\rho_i\right)ms}{1-\frac{\rho_2}{2}}$ means that the market price of the H-type machinery is larger than 2–4 times the costs of hired custom services for s units of land. Survey data suggest that the condition is likely to hold (see Section 4.1).

The sign of $\frac{\partial E(\pi_{HL})}{\partial \rho_1}$ is unambiguously negative, suggesting that the risk of losing small portions of leased land reduces the likelihood of investing in H-type machinery. Intuitively, even when the farm can continue employing the H-type machinery after losing a small portion of leased land, the efficiency advantage relative to the L-type machinery would be smaller on a smaller farm given the same amount of investment, $c_H + c_f s$.

The sign of $\frac{\partial E(\pi_{HL})}{\partial \rho_2}$ agrees with $-\left(\gamma^{\frac{1}{\alpha}}-1\right)\mu A^{\frac{1}{\alpha}}s - (1-\Delta_2)ms + kc_H$. The sign is not unambiguously negative because of the salvage value of H-type machinery that countervails the loss from not being able to employ the more efficient machinery in period 2. Again, considering settings where $E(\pi_{HN}) \geq 0$, I obtain inequality (4). Divide both sides by $(2-\Delta_1\rho_1-\rho_2)$, I have:

$$\left[\left(\gamma^{\frac{1}{\alpha}}-1\right)\mu A^{\frac{1}{\alpha}}+m\right]s \geq \frac{c_H + c_f s - \rho_2 k c_H}{2-\Delta_1\rho_1-\rho_2}.$$

Because $0 < k \leq \frac{1}{2}$ and $0 < \rho_i < 1$, the right-hand-side of inequality (6) is larger than

$$\frac{1}{2}\left(c_H + c_f s\right).$$

Knowing that the unit cost of improving infrastructure is considerably higher than the cost of mechanical services (i.e., $c_f \gg m$. See Section 4.1), it must be that $\frac{c_f}{2} - \Delta_2 m > 0$. Therefore,

$$\left(\gamma^{\frac{1}{\alpha}}-1\right)\mu A^{\frac{1}{\alpha}}s + (1-\Delta_2)ms = \left[\left(\gamma^{\frac{1}{\alpha}}-1\right)\mu A^{\frac{1}{\alpha}}+m\right]s - \Delta_2 ms > \frac{1}{2}c_H + \left(\frac{c_f}{2}-\Delta_2 m\right)s > kc_H.$$

I hence obtain:

$$-\left(\gamma^{\frac{1}{\alpha}}-1\right)\mu A^{\frac{1}{\alpha}}s - (1-\Delta_2)ms + kc_H < 0.$$

Therefore, $\frac{\partial E(\pi_{HL})}{\partial \rho_2} < 0$, meaning that the risk of losing land discourages investment in farm infrastructure and H-type machinery. This is the core insight of the model. Even if $\pi_H{}^* - \pi_L{}^* > 0$ in the risk-free scenario, the expected profit difference, $E(\pi_{HL})$, decreases in the insecurity of land rights and may fall negative if ρ_2 is sufficiently large.

3.2. Model extensions

A few extensions of the baseline model are discussed. First, instead of considering a risk of losing some leased plots, one could consider a risk of having some leased plots replaced by new plots due to land redistribution. Equivalently, that means the large farm could be able to maintain the size of farm at s in period 2 by costlessly finding new lessors even if some households stop leasing land to the farm. In the model, this translates to $\Delta_i = 0,\ i \in \{1,2\}$ and $E(\pi_{HL}) = (2-\rho_2)\left(\gamma^{\frac{1}{\alpha}} - 1\right)\mu A^{\frac{1}{\alpha}}s - \rho_2 ms - \left(c_H - \rho_2 kc_H + c_f s\right) + c_L$. Intuitively, the loss of a small portion of land no longer matters, or $\frac{\partial E(\pi_{HL})}{\partial \rho_1} = 0$, because the farm size remains at s and the use of L-type machinery is not affected. Losing a large portion of land still matters as H-type machinery cannot be used on the same size of farm because the newly leased plots in period 2 are not leveled or contiguous with other plots. Thus, a larger ρ_2 still tends to make the investment in the H-type machinery less profitable relative to investing in the L-type machinery and causes efficiency loss.

Second, should the insecurity in land rights be endogenous to capital investment, the conceptual model would imply different equilibrium behavior. Specifically, if the investment in attached assets could reduce the insecurity, farms would enjoy additional returns from enhancing farm infrastructure. This would increase the equilibrium investment in attached assets as well as H-type machinery. In the meantime, if there are credit constraints, relatively capital-rich farms would be more able to protect their land rights, while capital-constrained farms may shrink in size. This could mean a growing concentration of farmland to capital-rich farms in the long-run.

Third, if a large farm could mix the three investment options, the security of land tenure would affect the share of land put under each option. Intuition demonstrated by the baseline model stays that the share of land to which option 3 applies decreases in the risk of losing land. In reality, the mix of the three investment options is likely to be relevant, when there are credit constraints and the farm is unable to make sufficient investment in all fields or machinery in one time.

Finally, a large farm could have a fourth investment option: renting machinery instead of purchasing it. Yet, the farm in theory would be indifferent between renting the machinery and purchasing it, as long as the resale market for machinery is assumed competitive, so that the salvage value is set to fairly reflect the remaining value of a used machine. Key to the model is not whether a farm rents or purchases a machine, but whether returns to investing in infrastructure are fully captured by the farm. Thus, considering a fourth option does not change the central insight of the model. In fact, no evidence suggests that the rental market for farm machinery is active in China, though the market for custom mechanical services is, leaving the fourth option irrelevant.

4. Economic loss due to suboptimal capital investment

Though the comparative statics have shown the direction of effects of insecure land rights on farm investment, the magnitude of efficiency loss caused by suboptimal capital investment remains unknown, and whether the loss is economically significant is unclear. To obtain plausible estimations of the loss due to suboptimal investment, I calibrate the conceptual model based on actual operational parameters of grain harvesters and primary survey data of large farms in China. Brief background information of the survey data is offered, before the model is calibrated and the simulation outcomes are discussed.

4.1. Survey data

Chinese agricultural production is known for being dominated by small-scale household farms, with an average farm size smaller than 0.6 ha (Ministry of Agriculture of China (MOA), 2019), while medium/large-sized farms are emerging. Relatively large farms cultivate 30% of China's farmland (Ministry of Agriculture of China (MOA), 2019), many of sizes 6.6–13.2 ha, and are particularly important in agricultural markets, because they sell significantly higher portions of the outputs to markets compared with smallholder farms (Zeng & Liu, 2014).

These large farms provide an appropriate economic setting for calibrating the model for two main reasons. First, the farms are faced with nontrivial risks in land rights. Second, their land is of quality typically too low to support high-efficiency machinery.[6] Large farms in China can only lease but not purchase land. Their landlord-tenant relationships distinguish from classic landlord-tenant models in two important ways: 1) instead of a one-landlord-many-tenant relationship (Banerjee, Gertler, & Ghatak, 2002), one large farm in China leases from a large number of smallholder households, because most lessors are unable to provide more than an acre of land. 2) Lessors own no land and are effectively subleasing. Smallholder households only have insecure use rights in land under contracts with village collectives. Local governments may force sub-leases to end, either if they reallocate land to maintain egalitarian land holdings or expropriate land for nonfarm use. Lessor households may also terminate the sub-leases, when household members lose nonfarm jobs and return to farming (Ma, 2022).

[6] Farm infrastructure is poor, partly because government investments in farm infrastructure have been declining since the collective agricultural production was replaced by household-based farming in the early 1980s (Feder et al., 1992). After agricultural taxes were waived in 2006, local governments' budget was further tightened and their incentives for investing in public goods were weakened (Luo et al., 2007; Meng and Zhang, 2011).

I collected data of 49 large farms in a southwestern province of China, Sichuan, based on in-depth interviews with farm managers. The sample, though admittedly small, contains detailed information on hired labor, machinery use, farm assets, and investments that is unavailable elsewhere.[7] Despite the relatively small sample size, my data represent large farms in the region reasonably well as the summary statistics (see online appendix A) are consistent with other recent surveys of large farms in that region (Zeng & Liu, 2014; Zhang & Luo, 2018).

Observations of these farms align with key features of the model. First, these large farms operate on fields with poor infrastructure. In particular, plots are fragmented, unleveled, and disconnected. Because there are 2–3 cropping seasons a year, a large farm may lease land by season or by year. A farm leasing land seasonally on average contracts with 52 households, while a farm leasing yearly on average lease from 83 households. Not surprising that the average size of plots under either lease type is extremely small – barely larger than one sixth of an acre per plot. Second, the large farms hire large amounts of labor in each cropping season. Hiring farm labor is common for large farms regardless of their locations (Jayne et al., 2022) and is in sharp contrast against smallholder farms that almost exclusively rely on family labor.

Thirdly, these farms make considerable investment in movable assets. They purchase production machinery (e.g., tractors, planters, and harvesters), irrigation facilities (e.g., water pumps), and processing machinery (e.g., grain dryers). The mean value of machinery is 89,596 RMB (13,784 USD) by 2016. Most machines are small-size, low-efficiency, and second-hand. A few farms also invest in fields (e.g., leveling, reshaping, and merging plots and increasing biomass in soil). In online appendix A, I provide more details of the sampled farms. Econometric evidence shows that investment in fields increases the productivity of machinery, suggesting that productivity of movable and attached assets may be interdependent and supporting the key assumption of the conceptual model.

4.2. Parameterization

Operational parameters of farm machinery, such as power and speed, are difficult to estimate or find in general. Relatively easy to obtain are operational parameters and prices of grain harvesters which are widely used by large farms in China. I hence choose low-power grain harvesters to represent the L-type movable asset and high-power grain harvesters to represent the H-type in the model. The relative labor productivity of operating the two types of harvesters is the proxy for e_H in eq. (3).

In Table 1, the upper four rows contain information of four leading brands of low-power harvesters in China, while the lower two rows list features of two popular high-power harvesters. The low-power harvesters have small cut widths and sizes and are able to work on small plots and travel on narrow roads. In contrast, high-power harvesters have much larger cut widths and may only travel on sufficiently wide roads to reach fields with large plots.

High-power harvesters are considerably more expensive and also much more productive and durable. The column *cutting speed* reports the area harvested by a particular harvester in an hour and reflects the productivity of labor operating the harvester. The cutting speeds suggest that the labor productivity of high-power harvesters is some 1.5 to 2.9 times as high as that of low-power harvesters depending on field conditions. When running simulations, I first take the median efficiency gap between low- and high-power harvesters and vary the parameter in sensitivity tests.

In the calibrated model, each period represents a cropping season. The parameters are listed in Table 2. Land is measured by *mu* (i.e., 0.17 acre), and labor is measured by month. The unit of money is 1000 RMB. Given that both ρ_1 and ρ_2 affect the choice of option 3 in the negative way, I let $\rho_1 = 0$ and focus on ρ_2 in the simulations to highlight the effect of failing to continue using the H-type machinery. Under this setup, $E(\pi_{LN}) > 0 \ \forall \rho_2 \in (0, 1)$. Thus, the investment choice is effectively between investment options 2 and 3.[8] Note that m and m_O are the average machinery service price and non-labor cost of mechanical tillage, planting, and harvesting. Set $\Delta_2 s = 0.10s$ in the baseline. More details of deriving the parameter values are given in online appendix B.

4.3. Simulation outcomes: Baseline

Hereafter, I remove the subscript for ρ_2 and call it ρ as the only risk considered in the simulations. Optimal investment option changes in the probability of losing Δs units of land. In the baseline scenario, I set $\alpha = \frac{1}{2}$ and find that the farm invests in the H-type harvester as far as $\rho < 20\%$. As ρ turns 20%, the farm turns to investing in the L-type machinery. Hereafter, I call the probability that triggers a farm to switch from investing in the H-type to the L-type harvester the *switching probability* and denote it by ρ^*.

To estimate the efficiency loss, I compute the discounted two-period net production value which would be achieved under an investment option with no risk. If investing in the H-type harvester, the risk-free net production value is

$$npv_H = (1+\delta)\left[\mu A^{\frac{1}{\alpha}} \gamma^{\frac{1}{\alpha}} s - Fs\right] - \left(c_H + c_f s\right).$$

[7] Collecting a sample of this size is difficult given high logistics and communication costs of interviewing large-farm managers who run on tight schedules. On average, less than two interviews can be completed by one interviewer per day. This is in sharp contrast to surveying smallholder households. One interviewer can easily finish 6–7 interviews in a day.

[8] When $m - m_0$ is small, $E(\pi_{LN})$ could be negative, while $E(\pi_{HN})$ remains positive. In such a case, the choice is effectively between the options 1 and 3. The conclusion remains that farm investment in infrastructure and machinery tends to be inefficient as the insecurity in land rights grows. If the farm gives up option 3 and hires custom services provided by low-efficiency machinery, investment in low-efficiency machinery still increases in equilibrium (i.e., investment by custom service providers). There is again under-investment in infrastructure and over-investment in low-efficiency machinery.

Table 1
Features of low-power and high-power grain harvesters.

Brand	Max. power (*kW*)	Cut width (*meter*)	Feeding capacity (*kg/s*)	Cutting Speed (*mu/h*)	Price (1000 RMB)
Low-power harvesters					
AGCO 4LZ-3	75.0	2.51	3.0	5–7.5	75–91
Kubota 688Q	49.2	2.00	2.5	3–6.0	119–138
Lovol RC30	55.0	2.38	3.0	5–7.5	89–107
Yanmar 85	62.5	2.06	3.0	6–8.4	145–175
High-power harvesters					
Lovol GK100	162.0	5.34	10.0	9–21	521–680
JD C230	148.0	5.40	11.0	12–22	651–819

Note: JD stands for John Deere. *kW* stands for *kilowatts*, *kg/s* for kilogram per second, and *mu/h* for *mu* per hour. Information of low-power harvesters is relatively abundant. Harvester information is in Chinese.
AGCO 4LZ-3: https://www.nongjitong.com/product/6713.html,
Kubota 688Q: https://www.nongjitong.com/product/38774.html,
Lovol RC30: https://www.nongjitong.com/product/6307.html,
Yanmar AW85GR: https://www.nongjitong.com/product/yanmar_aw85gr_combine_harvester.html,
Lovol GK100: https://www.nongjitong.com/product/lovol_gk100-4lz-10_combine_harvester.html,
John Deere C230: https://www.nongjitong.com/product/6228.html.

Table 2
Parameters in the calibrated model.

Parameter	Definition	Value
s	Cultivation size in a season (*mu*)	229.6
Δ	A relatively large portion of leased land lost in period 2	10%
A	Technological efficiency for large farms	4.4
e_H	H-type machinery efficiency increase	1.85
c_L	Price of L-type machinery (1000 RMB)	30.0
c_H	Price of H-type machinery (1000 RMB)	113.3
c_f	Cost of merging and leveling plots per *mu*	3.3
m	Price of mechanical services per *mu*	0.11
m_O	Cost of using own machines per *mu*	0.03
F	Fixed cost for cultivating one *mu*, incl. Land rental	1.5
δ	Time discount factor	0.95
k	H-type machinery salvage value rate by the end of period 1	0.5
w	Monthly wage rate for farm labor (1000 RMB)	2.0

Note: Computed by the author. Details in online appendix B. Values are rounded to the tenth decimal point if appropriate.

Similarly, the risk-free net production value generated by the L-type harvester equals

$$npv_L = (1+\delta)\left[\mu A^{\frac{1}{\alpha}} s - Fs\right] - c_L.$$

Because option 3 would be optimal without risk, the difference between npv_H and npv_L can be interpreted as the forgone production value due to insecurity in land rights. In the baseline, npv_H is 448.4, while npv_L is 368.5. The former is 21.7% larger than the latter.

These values, of course, depends on the efficiency parameter e_H for the H-type machinery. To see how the baseline outcomes vary in e_H, I draw $npv_{HL}\% = \frac{npv_H - npv_L}{npv_L} \times 100\%$ for a series of e_H values in Fig. 1 with other parameters fixed at values listed in Table 2. Corresponding switching probabilities are drawn as well. When e_H increases, $npv_{HL}\%$ increases, which is implied by $\frac{\partial E(\pi_{HL})}{\partial e} > 0$ in Section 3.2. With e_H ranging from 1.80 to 1.90, the corresponding $npv_{HL}\%$ varies from 7.0% to 36.4%.

When the potential loss due to switching from H- to L-type machinery increases in e_H, so does ρ^*. Specifically, ρ^* increases from 6% to 31% as e_H goes from 1.80 to 1.90. That means, the switch is more and more unlikely as $npv_{HL}\%$ increases; yet, once it happens, larger loss follows.[9] Setting Δs to 0.00s (see discussion in Section 3.2), 0.05s, 0.15s, 0.20s, or 0.25s results in almost identical outcomes and hence are not plotted separately in the figure. Varying Δs has minimal impacts on simulation outcomes becuase Δs is not the main driver of investment decisions; what drives npv_{HL} most is ρ.

In reality, how high is the probability of losing some leased land in a period? My survey data suggest a 5-10% chance of experiencing land reallocation or expropriation each year for a smallholder. Assume that each household has a chance of 5% to experience changes in land rights in a period. If a large farm leases from 50 households, which is a reasonable number according to survey data, and each household contributes one unit of land. The probability of losing >2 households' land (i.e., $\geq$5%) is 45.9%, and the

[9] When e_H is sufficiently high, say equal 2.50, no $\rho^* < 1$ makes $E(\pi_{HL})$ negative. That means, when the H-type machinery is sufficiently more efficient than the L-type machinery, the efficiency loss caused by insecurity in land rights may be eliminated.

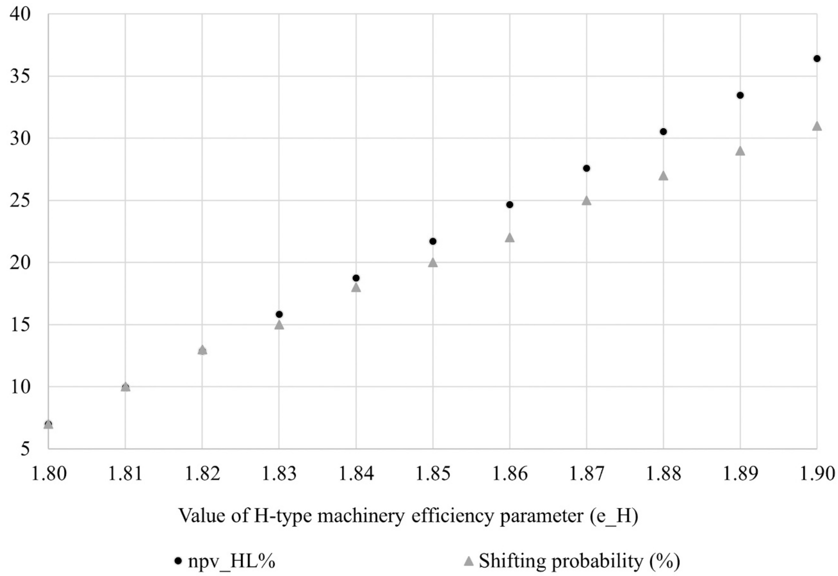


Fig. 1. Farm investment options and net production values with different efficiency advantages of the H-type machinery.
Note: Drawn by the author based on the calibrated model with α=0.5. The black dots refer to $npv_{HL}\% = \frac{npv_H - npv_L}{npv_L} \times 100\%$. Switching probability is represented by gray triangles for $\Delta = 10\%$. The horizontal axis measures the value of e_H in eq. (3).

probability of losing more 4 households' land (i.e., $\geq$10%) is 10.4%. If the large farm rents from 70 households, the probability of losing $\geq$5% of land is 46.6%, and the probability of losing $\geq$10% of land is 6.0%. If the chance of changing land rights is 6% (7%) per year, then probability of losing $\geq$10% of land quickly rises to 12.6% (21.7%) given 70 lessor households. That suggests, the switching probabilities in Fig. 1 lie in a reasonable range to be concerned by large farms. The overall conclusion, which is robust to e_H, is that large farms are fairly sensitive to risk of land rights and the economic loss due to the risk is nontrivial.

4.4. Simulation outcomes: Sensitivity checks

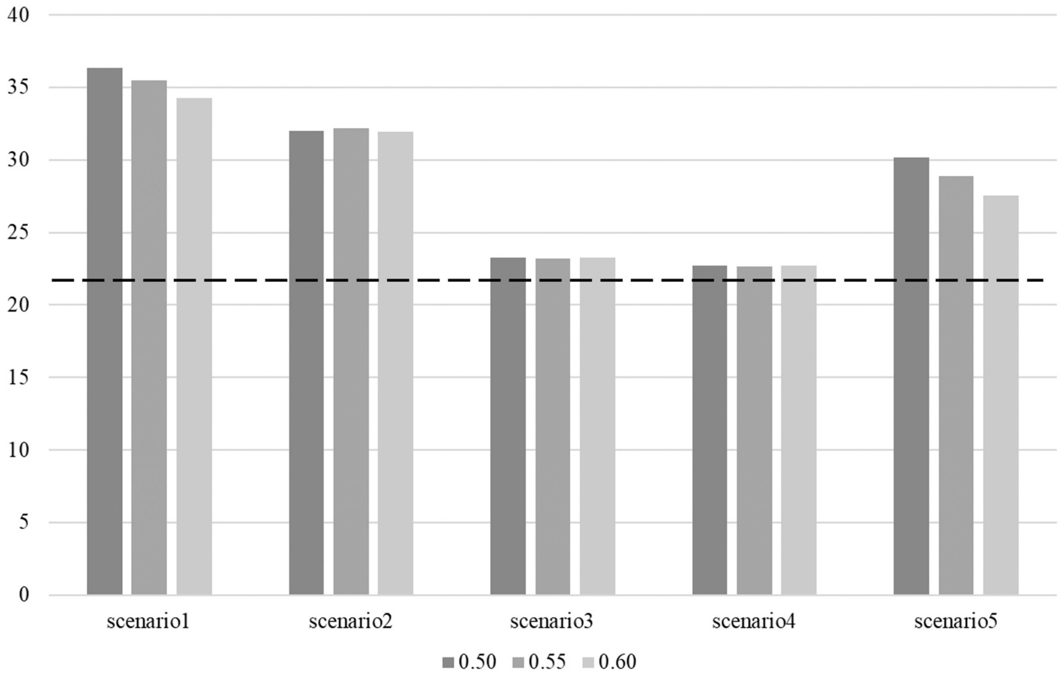
Referring to the comparative statics, I consider five alternative scenarios where the relative risk-free return to investing in the H-type machinery is even higher. In the following simulations, I fix e_H at 1.85, implying baseline $npv_{HL}\%$= 21.7% and ρ^* equal 20%. In each alternative scenario, I let one other parameter vary by 5% from its baseline value, making $E(\pi_{HL})$ more likely to be positive (i.e., giving the H-type machinery more advantage). In the first scenario, I let the technological multiplier of the large farm, A, increase from 4.4 to 4.6. With a larger A, ρ^* goes up to 38% (panel (a) of Fig. 2), and $npv_{HL}\%$ becomes 36.4% (panel (b) in Fig. 2). The changes echo the comparative statics derived in Section 3.1, $\frac{\partial E(\pi_{HL})}{\partial A} > 0$.

In the second scenario, I let the original quality of leased plots be relatively high, so that c_f decreases by 5% from 3.3 to 3.1. With this new parameter, ρ^* goes up to 29%, and $npv_{HL}\%$ becomes 32.0%. In the third scenario, I let the H-type harvester be cheaper, so that c_H=107.7. As a result, ρ^* becomes 21%, while $npv_{HL}\%$ goes up to 23.2%. In the fourth scenario, I let the size of leased land be larger, so that s=241.1. It turns out that ρ^* becomes 21%, while $npv_{HL}\%$ goes up to 22.7%. Finally, I let the wage rate for hired farm labor fall to w=1.9. This time, ρ^* increases to 30%, while $npv_{HL}\%$ goes up to 30.2%. Again, ρ^* and $npv_{HL}\%$ always change in the same direction. The overall conclusion from baseline outcomes stays, though increasing technological efficiency, lowering infrastructure and machinery costs, large farm sizes, and lowering wage rates bring down the sensitivity of investment options to insecure land rights.

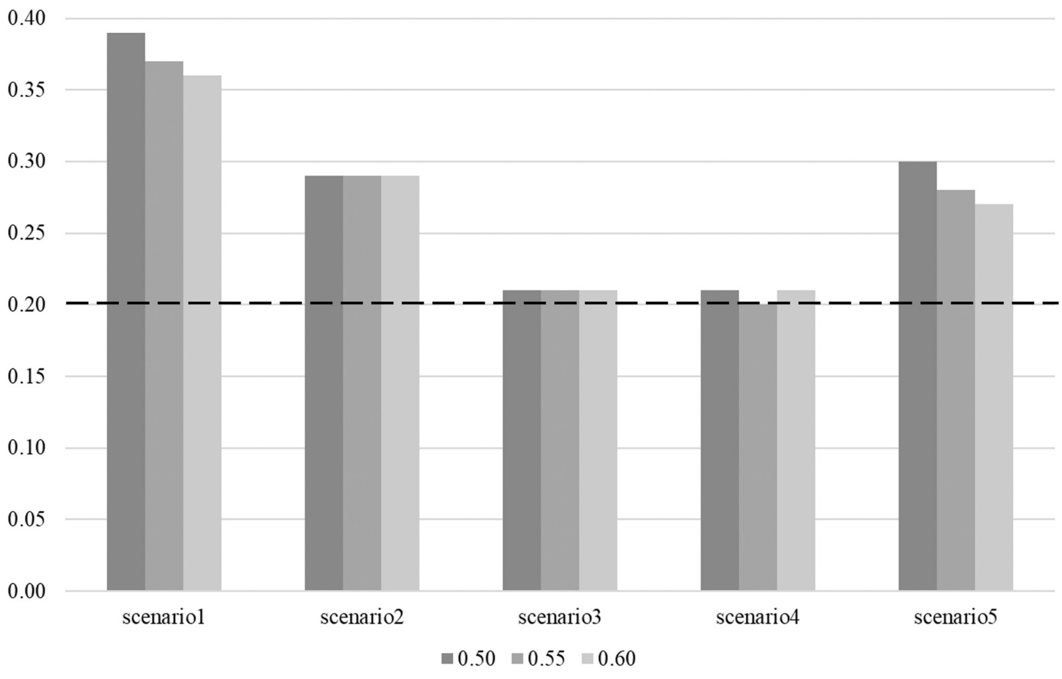
So far, the production function for simulations has been set as $As^{0.5}(el)^{0.5}$. For large farms, the relative contribution of labor to production may not be equal to that of land. Specifically, large farms are likely to be relatively land-intensive and have a relatively high output elasticity for land. To check how sensitive the results are to the form of production function, I re-run the simulations by setting α at 0.55 and to 0.60, respectively.

Letting $\alpha = 0.55$ (0.60), I increase e_H to 2.13 (2.51) for H-type machinery, so that $npv_{HL}\%$ =21.7% if $\rho = 0$ as in the basleine. The adjustment of e_H makes practical sense, too, because for farms using a more land-intensive technology, H-type machinery should have even higher efficiency than L-type machinery. As shown in Fig. 2, the value of α has limited impact on $npv_{HL}\%$ and ρ^* in all scenarios, because the heights of dark, medium, and light gray bars are always similar.

In summary, outcomes from the calibrated model suggest that insecurity in lease contracts can cause considerable loss in the net production value. Even under a fairly small risk of losing leased land, the farm may switch from investing in infrastructure and high-efficiency machinery to low-efficiency machinery. If the insecurity in land rights persists, fields operated by large farms tend to stay fragmented and with poor infrastructure. High-efficiency machinery hence cannot be used, even when large farms are active. Labor productivity on these farms would likely remain low relative to farms of similar sizes in developed economies, implying persistent farm income gaps across economies.



(a) Loss in net production values ($npv_{HL}\%$)



(b) Switching probabilities (ρ^*)

(caption on next page)

Fig. 2. Loss in net production values and switching probabilities under suboptimal investment in five scenarios.
Note: Drawn by the author based on the calibrated model. From dark to light gray bars, α=0.50, 0.55, and 0.60, respectively, in each panel. In panel (a), the vertical axis measures $npv_{HL}\% = \frac{npv_H - npv_L}{npv_L} \times 100\%$. In panel (b), the vertical axis shows the switching probability, ρ^*. The five scenarios are defined earlier in this section. With all other parameters fixed at values in Table 2, $A = 4.6$ in scenario 1, $c_f = 3.1$ in scenario 2, $c_H = 107.7$ in scenario 3, $s = 241.1$ in scenario 4, and $w = 1.9$ in scenario 5. The baseline $npv_{HL}\% = 21.7\%$ and $\rho^* = 20\%$ which are indicated by the dashed black lines in the corresponding panel.

5. Concluding remarks

I have argued that large farm investment in infrastructure plays a key role in determining their choices of movable assets, especially when public investment in infrastructure is limited. Even without credit constraints, the conceptual model shows that large farms are inclined to under-invest in attached assets and over-invest in low-efficiency movable assets facing insecure land rights. Using data of large farms in China, simulation outcomes suggest that a fairly small probability of losing land may induce a large farm to switch from investing in high-efficiency machinery to low-efficiency machinery. Net production value of large farms could increase by nontrivial amounts if the insecurity were eliminated.

The findings highlight another efficiency gain of eliminating tenure insecurity – efficiency of private investment in farm infrastructure and machinery. One might argue that the government could, without reforming land institutions, reduce inefficiency in farm investment by increasing public investment in farm infrastructure. The Chinese government, for instance, has tried to make a systematic enhancement of farm infrastructure without eliminating insecurity in land rights. The government launched the *Construction of Well-Facilitated Farmland* in 2011, aiming to make 53.4 million hectares or 40% of Chinese farmland "irrigated, leveled, contiguous, fertile, and equipped with paved roads and soil monitoring facilities by 2020."[10] Total government investment was expected to reach 550 billion RMB (about 85 billion USD) by 2016.

The government claimed that the construction of 26 million hectares of well-facilitated farmland was accomplished by the end of 2016. However, researchers find that the quality of so-called "well-facilitated farmland", though improved from the previous level, usually does not meet the target level. Farmland largely remains rather fragmented, disconnected, and with poor infrastructure. Zeng et al. (2018) show that improved field quality helps increase technological efficiency of farms and promote land rental activities in China. The improvement is limited, though, leaving the increase in farm efficiency statistically insignificant.

These quality issues might reflect the lack of self-sustainability of this project due to substantial financial burdens on central and local governments. Taking Sichuan Province where my survey data were collected as an example, the provincial government aims to improve the infrastructure of almost 3 million hectares of farmland by 2020. Given that the cost per hectares would be 44.5–50.1 thousand RMB (Fei et al., 2016), the total expenditure adds up to 13–15 billion RMB per year. The amount of capital investment is substantial relative to the annual budget for Sichuan's agricultural sector.[11] The government is likely to find it financially difficult to fund all or most of the construction.

The experience of China's state-led infrastructure-enhancement program echoes several negative experiences of public land-consolidation programs in other developing countries (Deininger et al., 2017). One problem is that producers are not incentivized to ensure the long-run viability of public consolidation programs if they do not have secure land rights. Changes brought by top-down investments are likely to be limited and may not sustain without active participation of producers, leaving consolidation without land reforms likely a second-best or partial solution to enhancing the quality of farmland (Oldenburg, 1990).

Provided with secure land rights and sufficient access to capital, private investment is likely to be more efficient, because farm managers who, compared with the government, have better information on costs and benefits of investing in highly heterogeneous fields that they work on. Sustainability of investments can be ensured by protecting the returns from attached assets to private investors. Eliminating insecurity in land rights and simultaneously improving rural credit markets may be a less costly and more efficient policy to carry out, making infrastructure-enhancement more self-sustainable in the long-run. Carefully designed subsidies from the government may also help accelerate the process of farmer-led improving farm infrastructure as indicated by the expansion of farmer-led irrigation investments in Asia and Africa (Kafle et al., 2022).

Funding sources

The work was supported by Henry A. Jastro Graduate Research Award and Banner Fellowship granted by the University of California, Davis.

[10] An earlier and similar government-subsidized enhancement of farm infrastructure, including plot merging and enhancing the irrigation system, was implemented in China during 1988–98. Positive effects of that project on cropping productivity are limited (Wu, Liu, & Davis, 2005). See news on the program of *Construction of Well-Facilitated Farmland*: http://www.ndrc.gov.cn/fzgggz/fzgh/ghwb/gjjgh/201705/t20170517_847668.html (in Chinese).

[11] For example, the 2017 annual budget was 23.2 billion RMB. Over half of the budget had to go to farm subsidies on large farms and cooperatives, poverty alleviation, agricultural insurance, and various public services in rural areas. Source: http://www.mof.gov.cn/zhuantihuigu/2017ysbghb/201703/t20170302_2545617.html (in Chinese).

Institutional review board (IRB) disclosure statement

Surveys described in this article were approved by IRB at the University of California, Davis. The IRB number is 905443–1.

Disclosure statement

The author declares that she has no relevant or material financial interests that relate to the research described in this article, nor does any of her close relative or partner. No other party has the right to review the paper prior to its circulation.

Data availability

Data and codes are all available at Harvard Dataverse (https://doi.org/10.7910/DVN/MXRJEX).

Acknowledgements

The article is based on the last two chapters of my Ph.D. Dissertation at University of California, Davis. I am extremely grateful to Richard Sexton, Lovell Jarvis, Kevin Novan, and Jeffrey Williams for insightful comments on earlier drafts. For helpful discussion and feedback, I thank Michael Delgado, Xinshen Diao, Xiaopeng Luo, Thomas Reardon, Jacob Ricker-Gilbert, Jerry Shively, Yang Yao, Heng Zhu, and audience at AAEA, CAER-IFPRI, CES, and MWIDEC conferences. I also thank Xiaomei Shen and Jianwei Zhao among other colleagues and government officials in China for their generous support to my field surveys in Sichuan Province. Any remaining errors are mine.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.chieco.2022.101909.

References

Akber, N., & Paltasingh, K. R. (2019). Is public investment complementary to private investment in Indian agriculture? Evidence from NARDL approach. *Agricultural Economics, 50*(5), 643–655. https://doi.org/10.1111/agec.12515

Ali, D. A., Deininger, K., & Ronchi, L. (2019). Costs and benefits of land fragmentation: Evidence from Rwanda. *World Bank Economic Review, 33*(3), 750–771. https://doi.org/10.1093/wber/lhx019

Bambio, Y., & Bouayad Agha, S. (2018). Land tenure security and investment: Does strength of land right really matter in rural Burkina Faso? *World Development, 111*, 130–147. https://doi.org/10.1016/j.worlddev.2018.06.026

Banerjee, A. V., Gertler, P. J., & Ghatak, M. (2002). Empowerment and efficiency: Tenancy reform in West Bengal. *Journal of Political Economy, 110*(2), 239–280. https://doi.org/10.1086/338744

Bardhan, P., Mookherjee, D., & Kumar, N. (2012). State-led or market-led green revolution? Role of private irrigation investment vis-a-vis local government programs in West Bengal's farm productivity growth. *Journal of Development Economics, 99*(2), 222–235. https://doi.org/10.1016/j.jdeveco.2012.06.003

Barrett, C. B., Reardon, T., Swinnen, J., & Zilberman, D. (2022). Agri-food value chain revolutions in low-and middle-income countries. *Journal of Economic Literature, 60*(4), 1316–1377. https://doi.org/10.1257/jel.20201539

Besley, T. (1995). Property rights and investment incentives: Theory and evidence from Ghana. *Journal of Political Economy, 103*(5), 903–937. https://doi.org/10.1086/262008

Binswanger, H. P., Khandker, S. R., & Rosenzweig, M. R. (1993). How infrastructure and financial institutions affect agricultural output and investment in India. *Journal of Development Economics, 41*(2), 337–366. https://doi.org/10.1016/0304-3878(93)90062-R

Blarel, B., Hazell, P., Place, F., & Quiggin, J. (1992). The economics of farm fragmentation: Evidence from Ghana and Rwanda. *World Bank Economic Review, 6*(2), 233–254. https://doi.org/10.1093/WBER/6.2.233

Carter, M. R., & Olinto, P. (2003). Getting institutions right for whom? Credit constraints and the impact of property rights on the quantity and composition of investment. *American Journal of Agricultural Economics, 85*(1), 173–186. https://doi.org/10.1111/1467-8276.00111

Deininger, K., Ali, D. A., & Alemu, T. (2011). Impacts of land certification on tenure security, investment, and land market participation: Evidence from Ethiopia. *Land Economics, 87*(2), 312–334. https://doi.org/10.3368/le.87.2.312

Deininger, K., & Jin, S. (2006). Tenure security and land-related investment: Evidence from Ethiopia. *European Economic Review, 50*(5), 1245–1277. https://doi.org/10.1016/j.euroecorev.2005.02.001

Deininger, K., Jin, S., & Ma, M. (2022). Structural transformation of the agricultural sector in low- and middle-income economies. *Annual Review of Resource Economics, 14*, 221–241. https://doi.org/10.1146/annurev-resource-111820-033252

Deininger, K., Monchuk, D., Nagarajan, H. K., & Singh, S. K. (2017). Does land fragmentation increase the cost of cultivation? Evidence from India. *Journal of Development Studies, 53*(1), 82–98. https://doi.org/10.1080/00220388.2016.1166210

Deininger, K., & Xia, F. (2016). Quantifying spillover effects from large land-based investment: The case of Mozambique. *World Development, 87*, 227–241. https://doi.org/10.1016/j.worlddev.2016.06.016

de Janvry, A., Emerick, K., Gonzalez-Navarro, M., & Sadoulet, E. (2015). Delinking land rights from land use: Certification and migration in Mexico. *American Economic Review, 105*(10), 3125–3149. https://doi.org/10.1257/aer.20130853

Dixit, R. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton University Press.

Feder, G., & Feeny, D. (1991). Land tenure and property rights: Theory and implications for development policy. *World Bank Economic Review, 5*(1), 135–153. https://doi.org/10.1093/wber/5.1.135

Feder, G., Lau, L. J., Lin, J. Y., & Luo, X. (1992). The determinants of farm investment and residential construction in post-reform China. *Economic Development and Cultural Change, 41*(1), 1–26. https://doi.org/10.1086/451992

Feder, G., & Onchan, T. (1987). Land ownership security and farm investment in Thailand. *American Journal of Agricultural Economics, 69*(2), 311–320. https://doi.org/10.2307/1242281

Fei, J., Ling, J., Wu, X., Li, H., Hu, J., Hu, Y., & Yang, R. (2016). Ji yu tu di zheng zhi jian ce jian guan xi tong de Gao biao zhun nong tian jian she zhuang kuang fen xi. [Analysis on construction of well-facilitated farmland based on land reclamation monitoring and supervision system]. *Transactions of the Chinese Society of Agricultural Engineering. 32*(3), 267–274.

Fenske, J. (2011). Land tenure and investment incentives: Evidence from West Africa. *Journal of Development Economics, 95*(2), 137–156. https://doi.org/10.1016/j.jdeveco.2010.05.001

Foster, A. D., & Rosenzweig, M. R. (2010). Barriers to farm profitability in India: Mechanization, scale and credit markets. In *Conference paper at conference agriculture for development-revisited, Berkeley, CA*.

Foster, A. D., & Rosenzweig, M. R. (2022). Are there too many farms in the world? Labor market transaction costs, machine capacities, and optimal farm size. *Journal of Political Economy, 130*(3), 636–680. https://doi.org/10.1086/717890

Goldstein, M., & Udry, C. (2008). The profits of power: Land rights and agricultural investment in Ghana. *Journal of Political Economy, 116*(6), 981–1022. https://doi.org/10.1086/595561

Jacoby, H., Li, G., & Rozelle, S. (2002). Hazards of expropriation: Tenure insecurity and investment in rural China. *American Economic Review, 92*(5), 1420–1447. https://doi.org/10.22004/ag.econ.11960

Jat, M. L., Gupta, R., Saharawat, Y. S., & Khosla, R. (2011). Layering precision land leveling and furrow irrigated raised bed planting: Productivity and input use efficiency of irrigated bread wheat in indo-Gangetic Plains. *American Journal of Plant Sciences, 2*(4), 578–588. https://doi.org/10.4236/ajps.2011.24069

Jayne, T. S., Wineman, A., Chamberlin, J., Muyanga, M., & Yeboah, F. K. (2022). Changing farm size distributions and agricultural transformation in sub-Saharan Africa. *Annual Review of Resource Economics, 14*, 109–130. https://doi.org/10.1146/annurev-resource-111220-025657

Kafle, K., Omotilewa, O., Leh, M., & Schmitter, P. (2022). Who is likely to benefit from public and private sector investments in farmer-led irrigation development? Evidence from Ethiopia. *Journal of Development Studies, 58*(1), 55–75. https://doi.org/10.1080/00220388.2021.1939866

Long, H. (2014). Land consolidation: An indispensable way of spatial restructuring in rural China. *Journal of Geographical Sciences, 24*, 211–225. https://doi.org/10.1007/s11442-014-1083-5

Luo, R., Zhang, L., Huang, J., & Rozelle, S. (2007). Elections, fiscal reform and public goods provision in rural China. *Journal of Comparative Economics, 35*(3), 583–611. https://doi.org/10.1016/j.jce.2007.03.008

Ma, M. (2022). Insecure land tenure, social protection, and resource misallocation: Evidence from China's agricultural sector. *Economic Development and Cultural Change, 70*(2), 835–863. https://doi.org/10.1086/713878

Mendelsohn, R. (1994). Property rights and tropical deforestation. *Oxford Economic Papers, 46*, 750–756. https://doi.org/10.1093/oep/46.Supplement_1.750

Meng, X., & Zhang, L. (2011). Democratic participation, fiscal reform and local governance: Empirical evidence on Chinese villages. *China Economic Review, 22*(1), 88–97. https://doi.org/10.1016/j.chieco.2010.09.001

Ministry of Agriculture of China (MOA). (2019, March 1). 《Guan yu cu jin xiao nong hu he xian dai nong ye fa zhan you ji xian jie de yi jian》 fa bu hui [*Supporting the Modernization of Smallholder Farms*]. Retrieved from http://www.moa.gov.cn/hd/zbft_news/xnhxdnyfz/ Accessed September 27, 2022.

Moschini, G., & Lapan, H. (1997). Intellectual property rights and the welfare effects of agricultural R&D. *American Journal of Agricultural Economics, 79*(4), 1229–1242. https://doi.org/10.2307/1244280

North, D. C., & Thomas, R. P. (1973). *The rise of the western world: A new economic history*. Cambridge University Press.

Oldenburg, P. (1990). Land consolidation as land reform in India. *World Development, 18*(2), 183–195. https://doi.org/10.1016/0305-750X(90)90047-2

Robinson, E. J. (2005). Reassessing the interaction between investment and tenure uncertainty. *Environment and Development Economics, 10*(2), 143–157. https://doi.org/10.1017/S1355770X04001895

Sheng, Y., Ding, J., & Huang, J. (2019). The relationship between farm size and productivity in agriculture: Evidence from maize production in northern China. *American Journal of Agricultural Economics, 101*(3), 790–806. https://doi.org/10.1093/ajae/aay104

Sunding, D., & Zilberman, D. (2001). The agricultural innovation process: Research and technology adoption in a changing agricultural sector. In *, Vol. 1. Handbook of agricultural economics* (pp. 207–262). Elsevier. https://ideas.repec.org/h/eee/hagchp/1-04.html.

Wang, X., Yamauchi, F., Huang, J., & Rozelle, S. (2020). What constrains mechanization in Chinese agriculture? Role of farm size and fragmentation. *China Economic Review, 62*, Article 101221. https://doi.org/10.1016/j.chieco.2018.09.002

Wu, Z., Liu, M., & Davis, J. (2005). Land consolidation and productivity in Chinese household crop production. *China Economic Review, 16*(1), 28–49. https://doi.org/10.1016/j.chieco.2004.06.010

Yamauchi, F. (2016). Rising real wages, mechanization and growing advantage of large farms: Evidence from Indonesia. *Food Policy, 58*, 62–69. https://doi.org/10.1016/j.foodpol.2015.11.004

Zeng, M., & Liu, C. (2014). Shui dao zhong zhi da hu de fa zhan xian zhuang, zhang ai ji dui ce. [Facts, challenges and solutions: Large-scale rice farms in Hunan Province, China]. *China Agricultural Information, 5*, 24–28.

Zeng, S., Zhu, F., Chen, F., Yu, M., Zhang, S., & Yang, Y. (2018). Assessing the impacts of land consolidation on agricultural technical efficiency of producers: A survey from Jiangsu Province, China. *Sustainability, 10*(7), 2490. https://doi.org/10.3390/su10072490

Zhang, L., & Luo, G. (2018). Xian shi yu chong gou: Wo guo liang shi shi du gui mo jing ji de kun jing yu bai tuo. Ji yu Chuan, Xiang 246 ge dao zuo da hu de diao cha. [Facts and reforms: Large-scale rice farms in Sichuan and Hunan provinces of China]. *Rural Economics, 5*, 28–33.

Zhang, X., & Fan, S. (2004). Public investment and regional inequality in rural China. *Agricultural Economics, 30*(2), 89–100. https://doi.org/10.1111/j.1574-0862.2004.tb00179.x

Zhang, X., Yang, J., & Thomas, R. (2017). Mechanization outsourcing clusters and division of labor in Chinese agriculture. *China Economic Review, 43*, 184–195. https://doi.org/10.1016/j.chieco.2017.01.012