# Capital Obsolescence and Agricultural Productivity*

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Abstract

This paper argues that accounting for capital-embodied technology greatly increases the importance of capital in explaining cross-country differences in agricultural labor productivity. To do so, we draw on a novel dataset of agricultural capital prices. We document that new capital is more expensive in richer countries, both in absolute terms and relative to old capital. A model of endogenous adoption of capital of different quality links these price differences to the path of capital-embodied technology. In particular, our model recovers the level of embodied technology from the price of new capital and the growth rate of embodied technology from the price of new capital relative to old capital. We then measure the stocks of quality-adjusted capital in agriculture for a sample of 16 countries at different stages of development. We find that adjusting for differences in quality almost doubles the importance of capital in accounting for cross-country differences in agricultural labor productivity: from 21% to 37%. In addition, improvements in capital quality have been an important source of agricultural labor productivity growth over the past 25 years, accounting for 21% and 35% of the productivity growth in poor and rich countries, respectively.

*JEL codes:* O13, O47, Q10.
*Keywords:* Agricultural labor productivity, capital-embodied technology, vintage capital.

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# 1 Introduction

Cross-country differences in agricultural labor productivity are large and overshadow those in other sectors of the economy. Restuccia et al. (2008), for example, report that the difference in output per worker in agriculture between the richest 5% of countries and the poorest 5% is 15 times larger than in non-agriculture. Because poorer countries employ most of their labor force in agriculture, understanding why agricultural productivity differences are so large is of primary importance to understanding cross-country differences in output per worker.[1] This paper is the first to study the role of capital-embodied technology in accounting for cross-country differences in agricultural labor productivity.

The mechanization of production has become an essential feature of modern agriculture across the world (Binswanger, 1986; Manuelli and Seshadri, 2014). A thorough assessment of the role of capital in agricultural labor productivity is limited by the absence of data on the technology embodied in capital. Tractors, for example, range from purely mechanical models that essentially push or pull objects to sophisticated models that include hydraulics, software, and GPS transmitters and are capable of planting seeds by themselves. This paper measures the technology embodied in agricultural equipment in 16 countries at different stages of development to advance our understanding of the sources of cross-country productivity differences in agriculture.

We focus our analysis on tractors, which are arguably the most important equipment used in modern agriculture. We start by constructing a novel dataset of prices of new and used tractors. Our dataset includes multiple cross sections covering 16 countries between 2007 and 2017. For each tractor priced in our sample, we observe hours of usage, age, and technical characteristics, such as horsepower, model, and brand. Two patterns emerge. First, rich countries have systematically higher prices for new equipment. For example, a new tractor traded in the United States is twice as expensive than a new tractor traded in Brazil. Second, the price of new equipment relative to old equipment (henceforth, relative price of new-to-old equipment) is higher in richer countries. For example, in Brazil a new tractor is worth 43% more than a 15-year-old tractor, whereas a new tractor in the United States is worth 84% more than a 15-year-old tractor.

We map these two patterns into cross-country differences in embodied technology and construct the first measure of agricultural equipment across countries that is adjusted for quality. Adjusting for quality, and therefore for the technology embodied in equipment,

[1] Caselli (2005) measures that cross-country differences in GDP per capita would virtually disappear if poorer countries achieved the same level of agricultural labor productivity as the United States.

is quantitatively important: It almost doubles the importance of equipment in accounting for cross-country differences in agricultural labor productivity, from 21% to 37%. Poorer countries have more tractors of lower quality than richer countries. Indeed, once adjusted for quality, the cross-country log-variance of equipment stocks becomes three times larger. We also find that the growth in embodied technology has been an important source of agricultural labor productivity growth over the past 25 years. The contribution of capital for labor productivity growth rises from 12% without quality-adjustment to 40% with quality-adjustment, on average across the countries in our sample.

Our inference of embodied technology from equipment prices relies on its link to economic obsolescence (Solow, 1960). The availability of newer high-quality equipment in the market affects the equilibrium prices of older low-quality equipment. For example, consider the feature of synchronized transmission in tractors that avoids double-clutching when changing gears. The value of such a feature is high when the best alternative technology requires gear dismounting and is minimal when self-driven tractors are available for production. Thus, the price of an equipment good reflects its technology relative to the best technology available at a point in time. We use the price of the new equipment in each country to recover the *level* of embodied technology, and the relative price of new-to-old equipment to recover the *growth rate* of embodied technology.

There are two major challenges in our inference. First, the relative price of new-to-old equipment reflects not only economic obsolescence but also physical depreciation. Physical depreciation results from usage and maintenance. Our dataset has information on hours of usage but not on maintenance expenses, and maintenance likely varies systematically with labor productivity. To make progress, we specify a model of endogenous usage, maintenance, and adoption of equipment of different qualities. For an empirically relevant shape of the physical depreciation function, we show that usage is a sufficient statistic for physical depreciation, because in equilibrium, the rate at which a good is maintained is proportional to the amount of hours it is used. Then, the effect of age on prices, controlling for hours of usage, is solely that of economic obsolescence. In particular, the price semi-elasticity to age is the inverse of the growth rate of embodied technology.

Second, cross-country differences in the price of the new equipment reflect differences in their quality — and thus in their level of embodied technology — and differences in the price per unit of quality. To disentangle these two, we again rely on the structural equations of our model. The Euler equation implies that the price per unit of quality relative to consumption depends on the marginal product of equipment per unit of quality. Along a balanced growth path, the latter can be written as a function of the physical depreciation rate and the economy-wide interest rate. We infer cross-country differences in the level of embodied technology from the price of new equipment, controlling for the marginal product per unit of quality and the price of consumption.

The next step is to recover quality-adjusted equipment stocks across countries. If we had information on the composition of these stocks by quality, then this step would be straightforward, but such information is not available. To make progress, we choose a functional form for the marginal product of equipment in agriculture. Then, we infer the value of the equipment stock in units of the level of embodied technology from the value of the marginal product of equipment, controlling for measured labor productivity, the level of embodied technology, other agricultural inputs, and their factor shares.

Our model and our inference rely on four key assumptions: (i) frictionless equipment markets, (ii) perfect substitutability of equipment of different qualities in production, (iii) a physical depreciation function whose natural logarithm displays constant elasticity in usage and maintenance, and (iv) a cost of equipment production that decreases in the level of embodied technology. The first two assumptions are commonly used in accounting exercises that involve other forms of capital, notably human capital (Caselli, 2005). They imply price differences across new equipment goods only reflect quality differences. The last two assumptions are supported empirically by estimates of the physical depreciation and maintenance profiles in durable goods (Hulten and Wykoff, 1981a; Morris, 1988), and by the persistent decay in the relative price of investment to consumption over time (Karabarbounis and Neiman, 2014). Importantly, assumption (iv) rationalizes economic obsolescence within the model.[2] Together, these four assumptions yield a structural interpretation of the variation of the log price of equipment with age and hours of usage and identify the path of embodied technology in a country.

In our measurement, we interpret price differences of equipment across countries as resulting from differences in quality and differences in the price per unit of quality. Price differences may also likely reflect international trade opportunities, as equipment is widely traded internationally (Eaton and Kortum, 2001), as well as noncompetitive behavior that arises, for example, from heterogenous demand elasticities across countries (Alessandria and Kaboski, 2011). In Section 6.1, we show that our identification strategy is robust to intro-

[2] A vintage capital model where capital of different vintages is combined with homogeneous labor in a Cobb-Douglas fashion aggregates to a neoclassical model with two sectors: a consumption sector and an equipment sector. Solow (1960) shows that productivity in the equipment sector grows proportionally to the level of technology embodied in capital, which is inversely proportional to economic obsolescence.

ducing international trade in equipment in our model. When home-trade shares are nonzero, as they are in the data, the absence of arbitrage opportunities in the domestic market allows us to link the price of any equipment to the domestic value of the marginal product of equipment per unit of quality. In Section 6.2, we estimate an elasticity of the price of identical tractors to agricultural labor productivity of 8%. When taking into account this elasticity along with the 23% elasticity for tradable consumption estimated by Alessandria and Kaboski (2011), quality-adjusted equipment accounts for 54% of cross-country disparities in agricultural labor productivity, 17 percentage points above our benchmark.

**Related literature.** Our paper relates to the literature that emphasizes the role of agricultural productivity in explaining income disparities across countries. Cross-country differences in agricultural productivity may arise due to disparities in the intensity of factors' use (Restuccia et al., 2008; Donovan, 2014; Chen, 2020), sectorial differences in hours and human capital (Gollin et al., 2014; Lagakos and Waugh, 2013), disparities in the returns to human capital across sectors (Herrendorf and Schoellman, 2015), and disparities in the incidence of size-dependent distortions on farms (Adamopoulos and Restuccia, 2014). Disparities in the adoption patterns of technology embodied in equipment — and hence, in the quality of the physical capital used in production — remain unaccounted for. This paper bridges the gap.

Currently available data on agricultural equipment stocks across countries do not adjust for quality (Larson et al., 2000 and The Food and Agricultural Organization Statistical Database, FAOSTAT). We provide this adjustment using recent data and show its first order implications for measuring the role of equipment in labor productivity. Methodologically, we contribute to the measurement of quality-adjusted equipment stocks by providing inference from the model-predicted relationship between equipment price and age in a cross-section. The standard approach to constructing quality-adjusted stocks relies on time series of prices of durable goods and their characteristics (Gordon, 1987). We circumvent this data requirement by showing how a cross-section of prices can be equally informative on the path of embodied technology.[3]

Finally, our paper relates to the literature that studies the link between technology adoption and capital obsolescence in models of vintage capital.[4] We present a tractable framework

[3]Empirically, the paper closest to ours is by Gort et al. (1999), who use the cross section of rental rates of commercial buildings to infer the rate of improvement in the quality of structures. In our paper, we use the cross section of prices.

[4]See, for example, Benhabib and Rustichini (1991), Jovanovic and Rob (1997); Greenwood and Jovanovic (2001) and Jovanovic and Yatsenko (2012). Boucekkine et al. (2011) build an extensive review of this literature.

that can be mapped into the standard two-sector economy, as in Greenwood et al. (1997).

The remainder of the paper is organized as follows. Section 2 documents the relationship between equipment prices and age across countries; Section 3 describes the model; Section 4 outlines our identification strategy and presents the inferred path of quality-adjusted equipment stocks; Section 5 quantifies the importance of this path for agricultural productivity; Section 6 discusses the robustness of our identification strategy and findings to international trade in equipment and a frictional equipment-producing sector; Section 7 concludes.

## 2 The age-price profile of equipment across countries

In this section, we document systematic differences across countries in the effect of age on tractor prices. We later argue that these differences are a symptom of differences in the path of embodied technology.

The tractor is a ubiquitous implement in modern agricultural production. Its use spans through the production processes of many agricultural products. It is higher in the production of staple grains and lower in that of tree crops and in the raising of livestock. In addition, tractors are complementary to many other equipment goods, such as harvesters and tillage equipment, which are used for a broad set of agricultural outputs.

We collect data on new and old tractor prices for 16 countries over different years between 2007 and 2017. We use information provided by a major data publisher that gathers information on the characteristics and prices of various types of agricultural equipment available around the world. For two countries in our sample, India and China, we instead use scraped data from online catalogs. The dataset consists of more than 600,000 observations on catalouge prices, age, model, manufacturer, horsepower (HP), hours of usage, and location of the tractor sold. The average tractor in the sample is 10 years old and has 140 HP. For the countries for which we have access to Agricultural Censuses — United States, Canada, Mexico and Brazil — our dataset spans across all tractors' age and HP brackets, although it tends to oversample among tractors with high HP. Summary statistics of our dataset are in Table IV, in the Appendix.[5]

Our econometric strategy consists of specifying a tractor's $o$ catalogue price in year $t$ in country $i$ as a function of its age and other features. We regress the natural logarithm of a tractor's price, $\ln(p^e_{oit})$, on its age $a_{oit}$, its accumulated hours of usage $h_{oit}$, a dummy variable

[5]For a subsample of our dataset we observe transaction prices, along with catalogue prices. In the Online Appendix, we show that our estimates of the age-price profile are robust to using these two set of prices.

for its manufacturer $MANU_{oit}$, and its horsepower $HP_{oit}$:

$$\ln\left(p^{e}_{oit}\right) = \gamma_{1it} + \gamma_{2i} a_{oit} + \gamma_{3i} h_{oit} + \gamma_4 MANU_{oit} + \gamma_5 \frac{HP^{\xi}_{oit} - 1}{\xi} + \epsilon_{oit}, \tag{1}$$

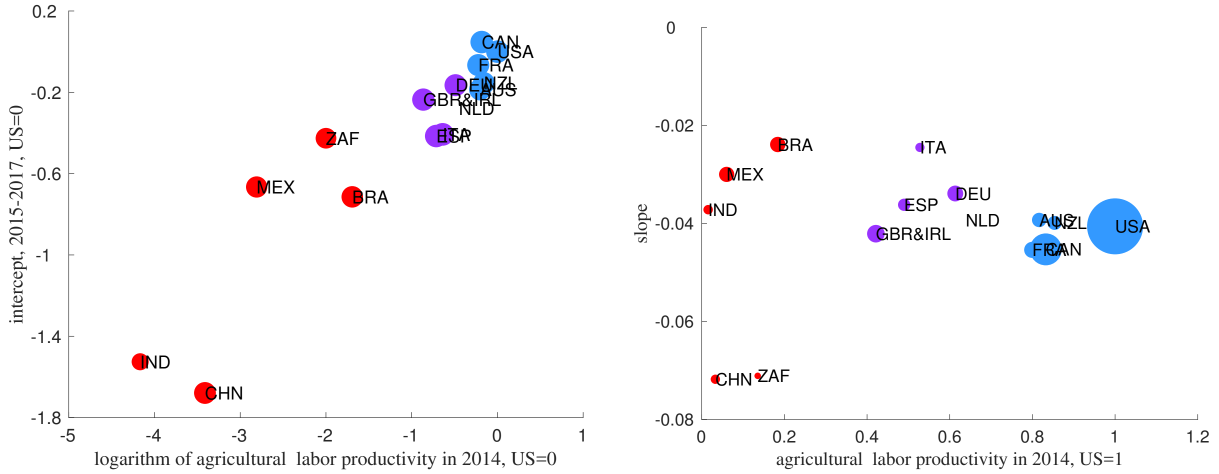
where $\xi$ is the parameter of a Box-Cox transformation and $\epsilon_{oit}$ is an error term, normally distributed, mean-zero, and i.i.d. across observations. We refer to the age-price profile in a country by the parameters that govern it: $\gamma_{1it}, \gamma_{2i}, \gamma_{3i}, \gamma_4, \gamma_5$, and $\xi$. The intercept of the profile is $\gamma_{1it}$ and the slope of the profile is $\gamma_{2i}$. These two coefficients describe the relationship between the price of a tractor and age in a cross section.

Regression equation 1 allows for three sources of cross-country heterogeneity in the coefficients: the intercept and the slope of the age-price profile, and the coefficient on hours of usage. The intercept of the profile reflects cross-country differences in the logarithm of the price of a new tractor at a given point in time. It is a function of both the quality of such tractor and of country-specific characteristics that affect the overall price level, such as the availability of newer embodied technology and agricultural production inputs. The slope of the profile is the price semi-elasticity to age. It is a function of economic obsolescence and reflects the gap in the quality of a tractor to the best in the economy. The coefficient on hours of usage is the price semi-elasticity to usage. It reflects physical depreciation per hour of usage and thus maintenance on the tractor. We include this additional source of cross-country heterogeneity because the labor cost of maintenance is lower in poorer countries and therefore physical depreciation per hour of usage is likely lower too.[6]

We estimate equation 1 in a pooled regression via maximum likelihood; see the Online Appendix for details. Our statistical model accounts for 89.5% of the variation in tractor prices observed in the data. Table V, column (2), and Table VI report the estimated coefficients. Figure I plots agricultural labor productivity against the estimates of the intercept and of the slope of the age-price profile across the countries in our sample. The size of each dot in the scatter plots is proportional to the inverse of the standard error in the estimated parameter; larger dots indicate more precise estimates.

The intercept of the age-price profile is strongly correlated with agricultural labor productivity. Richer countries display a systematically higher price of new equipment. A 1-log-point increase in labor productivity is associated with a 36.1% increase in the price of the new tractors. In contrast, the slope of the profile is negative in all countries and lies between -2% and -8%. If we exclude the two countries with an exceptionally strong decrease in the price

[6]For example, the purchasing-power-parity adjusted wages of automobile mechanics in the United States is 7 times larger than in India in 2000 (Occupational Wages around the World database).




(a) Intercept

(b) Slope

Figure I: Age-price profiles: intercept and slope.

Panel (a) plots the country-year coefficient in equation (1), $\gamma_{1it}$, relative to the United States in 2015-2017 against the logarithm of labor productivity in agriculture in 2014; Panel (b) plots the age coefficient in equation (1), $\gamma_{2i}$, against labor productivity in agriculture in 2014. The size of the dot is proportional to the inverse of the standard error in the estimation of each coefficient. Countries are color-coded in blue when their agricultural labor productivity in 2014 is more than two thirds that of the United States, in red if their agricultural labor productivity in 2014 is less than one-third of that in the United States, and in violet in the remaining case. Country are labelled by the alpha-3 ISO code. Source: FAOSTAT and our own computations based on catalog prices of tractors.

with age (China and South Africa), in countries with higher agricultural labor productivity, the prices of new tractors are larger relative to the prices of old tractors (a more negative slope). The correlation between the slope of the profile and labor productivity is -0.58.

Figure II combines the estimates of the intercept and slope to plot the complete age-price profile for the countries in our sample. The remainder of the paper links these profiles to the path of embodied technology across countries.

**Robustness.** We test the robustness of our empirical findings to alternative specifications of the regression equation 1. Implementation details are described in Appendix A. We first generalize regression equation 1 to allow for an arbitrary shape of the decay of prices with age and hours of usage. We estimate a Box-Cox transformation on the price and allow the data to determine the functional form of the shape.[7] We find the estimates of the slope and the intercept of the profile in the Box-Cox model are very close to the ones estimated by imposing a logarithmic shape. The slope of the profile is 0.5 percentage points (pp) less negative than in our benchmark on average (comparing columns (1) and (6) in Table VII). The

[7] Wu and Perry (2004) find the Box-Cox model best explains the variability of the price of used agricultural tractors, although much less complicated models perform nearly as well.

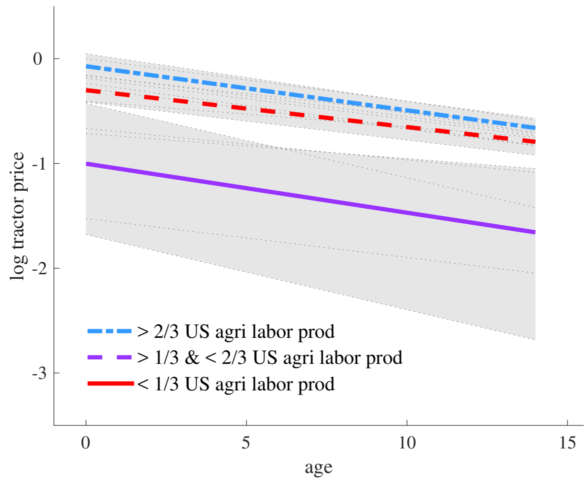



Figure II: Age-price profiles.
The figure plots the logarithm of the price of a tractor against age, for the countries in our sample. The price of a new tractor in the United States is normalized to 1. Countries are grouped by their agricultural labor productivity in 2014, and the average of each group is highlighted. Ordered by the intercepts from top to bottom, the age-price profiles belong to: Canada, the United States, France, New Zealand, Germany, Australia, Great Britain and Ireland, the Netherlands, Italy, Spain, South Africa, Mexico, Brazil, India, and China. Source: FAOSTAT and our own computations based on tractors' catalogue prices.

cross-country variance of the profile intercept decreases from 0.27 in our benchmark to 0.21 in the Box-Cox model (see Table VIII). These results suggest that imposing a logarithmic shape is quantitatively inconsequential for our measurement of the age-price profile. Hulten and Wykoff (1981a) also document an approximately semi-log form for the effect of age on the prices of durable goods, including tractors.

We then include two additional controls that may influence the price of a tractor and bias our estimates: the type of cultivated crops and the wages of repair workers. First, the degree of mechanical wear in a tractor depends on the geographical characteristics of the plot where it is operated, which is correlated with the cultivated crop. Second, the resale price of a tractor likely falls with the cost of repairs, a large component of which is the labor cost. When both controls are included, the slope of the age-price profile becomes slightly more negative by 0.05 pp, on average, and the cross-country variance of the profile intercept remains unchanged at 0.029 (comparing columns (2) and (5) in Table VII).

# 3 A model of equipment quality, usage, and maintenance

We formalize the link between the empirical findings documented in the previous section and the path of technology embodied in equipment within a general equilibrium model. We characterize the price of equipment in relation to the two mechanisms that shape its evolution with age: economic obsolescence and physical depreciation. The adoption of embodied technology, as well as usage, and maintenance of equipment are decisions of the agents in the model.

For brevity, our model presents a single country in autarky. We develop implications for cross-country differences in the age-price profile in Section 4.2. We discuss the implications of international trade in equipment in Section 6.1.

## 3.1 Environment

Time is discrete and indexed by $t$. The economy consists of two sectors: a farming sector and an equipment-producing sector. The farming sector consists of a continuum of homogeneous farms that produce a final consumption good — that is, agricultural products. The equipment-producing sector consists of a continuum of homogeneous firms that produce investment goods — that is, equipment and maintenance services. In addition, the economy is populated by a continuum of homogeneous households of measure 1 that consume the final good and accumulate equipment. They rent equipment, labor, and land to the farms in the economy.

A continuum of equipment vintages indexed by $j$ is differentiated by their quality, $q_j \in (0, \infty)$. Higher-quality vintages have higher indexes. We conceptualize quality as a factor that converts raw quantities of equipment into efficiency units in farming production. Therefore, quality describes the technology embodied in equipment. We say a stock $k_j$ of equipment of vintage $j$ can supply $q_j k_j$ efficiency units when used in production, or that $q_j k_j$ are the efficiency units embedded in $k_j$ units of vintage $j$.

Equipment can be utilized for a finite amount of hours at each point in time. We normalize hours at each point in time to 1 and refer to the number of hours equipment is utilized as the utilization rate, $u_{jt} \in [0, 1]$. The number of services each unit of equipment provides depends on its utilization rate. A stock $k_j$ supplies $u_j k_j$ equipment services to farming production. We refer to $\kappa_j \equiv u_j k_j \leq k_j$ as equipment services, and to $q_j \kappa_j$ as the efficiency units associated with these services. Utilization induces physical depreciation on equipment, but the household can counteract this loss by purchasing parts for maintenance or by investing in additional equipment. The household provides any needed maintenance labor itself.

Farms produce the final consumption good using a decreasing return technology in land, labor, and equipment services. Improvements in the technology take two forms: embodied in equipment and disembodied. We take the dynamics of disembodied technology as exogenous and associate it with a total factor productivity (TFP) term that evolves deterministically over time. We endogenize the adoption of embodied technology by allowing farmers to make costly investments to operate vintages with higher embodied technology. We define the level of embodied technology of a farm to be the quality of the highest vintage it can operate, $q_{\hat{j}}$. We refer to the level of embodied technology as *the level of embodiment* and to its growth rate as *the growth rate of embodiment*.[8]

Last, we assume all markets are complete and there are no frictions.

## 3.2 The farming sector

Each farm has an initial level of embodiment. If a farm with level of embodiment $q_{\hat{j}_t}$ employs $n_t$ units of labor, rents $l_t$ units of land, and rents $\kappa_{jt}$ equipment services, it produces output according to

$$y_t = \Phi_t^{1-\alpha_k}(f(\{q_j\kappa_{jt}\}_{j\in A_t}))^{\alpha_k} l_t^{\alpha_l} n_t^{\alpha_n}, \quad \text{for } \alpha_k + \alpha_l + \alpha_n \equiv \alpha < 1, \tag{2}$$

where $A_t \equiv \left\{ j : j \leq \hat{j}_t \right\}$ is the set of vintages that the farm can operate, $f$ is an aggregator of equipment services of different vintages, and $\Phi_t$ is TFP, which grows at rate $\mu_\Phi$, $\Phi_{t+1} = \Phi_t(1+\mu_\Phi)$.[9]

A farm can advance its embodied technology between periods $t$ and $t+1$ by paying an adoption cost at time $t$. The adoption cost is expenses incurred when adjusting production techniques to be able to operate higher quality vintages. For example, the introduction of a self-driven tractor on a farm requires mapping the path of the tractor from the shed into the field. The adoption cost depends on (1) the farm's level of embodied technology relative to the frontier technology at time $t$ and (2) on the size of the barriers to technology adoption in the economy. Barriers to technology adoption relate to the suitability of the technology

[8] Alternatively, one could define the embodied technology of a farm as the quality of the average vintage that a farm operates.

[9] In the production function, we exponentiate TFP to $1-\alpha_k$ for notational ease in the algebraic derivations of the balanced growth path of the economy.

to the farms. For example, the cost of monitoring the path of a self-driven tractor might be higher when there are only a few trained workers available.

The worldwide frontier technology for equipment is vintage $J_t$ with quality $q_{J_t}$. We assume this frontier grows exogenously at rate $\mu$, denoted as

$$q_{J_{t+1}} = q_{J_t}(1+\mu). \tag{3}$$

Given the level of the frontier at time $t$ and given a farm's current level of embodiment, $q_{\hat{j}_t}$, the cost of upgrading embodied technology to $q_{\hat{j}_{t+1}}$ in units of the final good is

$$x_t^q = \Phi_t \omega \int_{q_{\hat{j}_t}}^{q_{\hat{j}_{t+1}}} \left(\frac{s}{q_{J_t}}\right)^{\theta} ds, \qquad (\theta, \omega) > 0, \tag{4}$$

where $\omega$ indexes barriers to technology adoption. We borrow this specification of the adoption cost from Parente and Prescott (1994). The elasticity of the cost to the quality of the vintage adopted is a function of the shape parameter $\theta$. It is cheaper to improve technology when the frontier technology is higher. This implies that at the optimum, given the current level of technology, the rate of adoption will be higher the larger the gap to the frontier. Finally, we scale the cost with farms' TFP so that it does not become negligible over time as TFP grows.

The problem of a farm with embodied technology $q_{\hat{j}_t}$ and TFP $\Phi_t$ is to maximize the present discounted value of its profits given the sequences of labor, land, and equipment rental prices, namely $\{w_t, r_{lt}, \{r_{jt}\}_{j\in A_t}\}_{t=0}^{\infty}$:

$$\max_{\left\{l_t, n_t, \{\kappa_{jt}\}_{j\in A_t}, q_{\hat{j}_{t+1}}, x_t^q\right\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \frac{1}{\prod_{s=0}^{t} R_s} \left(y_t - x_t^q - w_t n_t - r_{lt} l_t - \int_{j\in A_t} r_{jt}\kappa_{jt} dj\right), \tag{5}$$

subject to equations 2 and 4; an initial level of embodiment, $q_{\hat{j}_0}$; and the laws of motion for the world technology frontier, equation 3; and for TFP. The farm discounts future profits at the market interest rate, $R_t$.

**Output of the farming sector.** Aggregate output of the farming sector is a linear aggregator of the farms' output. Although we assume decreasing returns to factors of production in each farm, the economy is described by a convex cone. As in Hornstein and Prescott (1993), if all factors of production increase proportionally, so does the number of production units and aggregate output. We normalize the measure of farms to 1. Aggregate output is

$$Y_t = \Phi_t^{1-\alpha_k} f\left(\{q_j \kappa_{jt}\}_{j \in A_t}\right)^{\alpha_k} L_t^{\alpha_l} N_t^{\alpha_n},$$

where $L_t$ and $N_t$ are aggregate land and labor, respectively.

## 3.3 Households

A households maximize its present-discounted value of lifetime utility from consumption,

$$\sum_{t=0}^{\infty} \beta^t \ln(c_t), \tag{6}$$

where $\beta$ is the preference discount factor and $\ln(c_t)$ is the per-period utility. Each period, households are endowed with $N$ units of productive time and $L$ units of land. They supply both factors of production inelastically to the market and receive income $r_{lt}L$ from land and income $w_t N$ from labor.

Households own the stock of equipment vintages in the economy and make utilization and maintenance decisions over these stocks. In each period, they choose the quantity of equipment services to rent to the market. A household who owns a stock $k_{jt}$ of equipment of vintage $j$ and chooses to utilize it at rate $u_{jt}$, rents $u_{jt}k_{jt}$ equipment services at rental rate $r_{jt}$, in period $t$. Utilization induces physical depreciation on equipment in the form of wear and tear. Households counteract this wear and tear by purchasing maintenance parts $m_{jt}k_{jt}$ at price $p_{jt}$, with $m_{jt} \in [0, 1]$ denoting maintenance per unit of equipment. A physical depreciation function $\delta(u, m)$ maps utilization and maintenance rates into the rate of physical depreciation.[10]

Finally, households are endowed with a distribution of equipment vintages at time $t = 0$, $k_{j0} \geq 0$, with strict inequality for a non-zero measure of vintages. They accumulate new stocks of vintage $j$ by purchasing $x_{jt}$ units at price $p_{jt}$. The law of motion of the equipment stock of a vintage $j$ is:

$$k_{jt+1} = x_{jt} + k_{jt}(1 - \delta(u_{jt}, m_{jt})), \quad \text{for all } j \in A_{t+1}^h, \tag{7}$$

where $A_t^h$ is the set of vintages that the household owns at period $t$.

[10] A few papers allow for both endogenous utilization and maintenance, because typically the decision of utilization is interpreted as net of maintenance. One example in the business-cycle literature that allows for both margins is Albonico et al. (2014), which embeds Burnside and Eichenbaum (1996) and McGrattan and Schmitz (1999) as special cases.

We use the consumption good as the numeraire of the economy and normalize its price to 1. The household budget constraint reads as follows:

$$c_t + \int_{j \in A^h_{t+1}} p_{jt} \left( x_{jt} + m_{jt} k_{jt} \right) dj \leq \int_{j \in A^h_t} r_{jt} u_{jt} k_{jt} dj + w_t N + r_{lt} L + \Pi_t, \tag{8}$$

where $\Pi_t$ are aggregate profits of the farming sector.

The problem of the household is to maximize utility (equation 6) subject to the budget constraint (equation 8), the law of motion for equipment (equation 7), and an initial distribution of equipment vintages.

## 3.4 Equipment-producing sector

Perfectly competitive firms purchase the final good and use a linear technology to transform it into investment goods of different vintages, which they sell at price $p_{jt}$. Equipment producers maximize profits. The profit function is

$$\max_{y^x_{jt}} \quad y^x_{jt} \left( p_{jt} - q^{\alpha_k}_{\hat{j}_t} \frac{q_j}{q_{\hat{j}_t}} \right), \tag{9}$$

where $y^x_{jt}$ is the quantity of investment goods of vintage $j$ produced.

The marginal cost of producing investment goods has two features. First, it scales with the quality of the vintage being produced. Higher vintages are more expensive, proportional to the higher quality they provide. Second, given a vintage, the marginal cost of production decreases with the level of embodiment in the economy, because of investment-specific technical change. This feature rationalizes economic obsolescence within the model. In particular, the equipment-producing firms find it profitable to produce vintages of higher quality, as farms adopt them. The availability of these higher vintages in the market induces economic obsolescence on the lower-quality vintages.[11]

[11] Our modeling of economic obsolescence via investment-specific technological change creates a mapping between our theoretical framework and that in Greenwood et al. (1997). The state of the technology for producing equipment in their model, $q$, corresponds to a transformation of the level of embodiment in our model, $q^{1-\alpha_k}_{\hat{j}}$. We discuss this mapping in the Online Appendix.

## 3.5 Equilibrium equipment price schedule

For brevity, we define the equilibrium in Appendix C. Here, we describe assumptions on the farming production technology and on the physical depreciation function, as well as features of the equilibrium allocation, that allow us to connect model prices to their empirical counterpart and infer the path of embodied technology.

The Euler equation characterizes the price of a unit of equipment as a function of the utilization rate, the maintenance rate, and the per-period payoff to the household, $\Psi_{jt}$:

$$p_{jt} = \frac{1}{R_{t+1}} \left[ \Psi_{jt+1} + (1 - \delta(u_{jt+1}, m_{jt+1})) p_{jt+1} \right]. \quad \text{(Euler)}$$

The per-period payoff includes the rental value of equipment services, $r_{jt}u_t$, net of maintenance expenses, $m_t p_{jt}$:

$$\Psi_{jt} = r_{jt}u_t - m_t p_{jt}. \quad (10)$$

In our measurement, we use the equilibrium price of a unit of equipment to construct prices of new and old equipment by arbitrage (see Section 4.1). The key features of these prices on which our measurement relies are proportionality in equipment quality and exponential decay in the utilization rate. The following two assumptions are sufficient for the model to generate equilibrium prices that display these two characteristics.

**Assumption 1.** *Equipment services of different vintages are perfect substitutes in farming production,*

$$f(\{q_j \kappa_{jt}\}_{j \in A_t}) = \int_{j \in A_t} q_j \kappa_{jt} dj.$$

This assumption implies that the marginal product of equipment services is proportional to the quality of the vintage under frictionless rental markets. The equilibrium price of equipment inherits this property, given the specification of the Euler equation. Assumption 1 is commonly used in accounting exercises that involve other forms of capital, notably human capital (see, among others, Caselli, 2005).

**Assumption 2.** *The physical depreciation function satisfies*

$$\delta(u_{jt}, m_{jt}) = u_{jt} e^{-\mathcal{G}(u_{jt}, m_{jt})}, \quad \textit{for} \ \mathcal{G}(u_{jt}, m_{jt}) : [0, 1]^2 \to [0, \infty].$$

*The function $\mathcal{G}(u_{jt}, m_{jt})$ increases with the maintenance rate, decreases with the utilization rate, and displays constant elasticity in the utilization rate.*[12]

[12]The exponential transformation assures the depreciation rate is between 0 and 1. An example of a

This assumption characterizes a class of physical depreciation functions for which the equilibrium of the model is consistent with an exponential decay of equipment prices in utilization rates, as displayed in our dataset (see the robustness discussion in Section 2) and as most commonly observed for durable goods (Hulten and Wykoff, 1981b).

**Usage and maintenance.** The next proposition delivers two important results for our inference.

**Proposition 1** (Usage and maintenance)**.** *(i) The physical depreciation rate per unit of utilization, $e^{-\mathcal{G}(u_{jt},m_{jt})}$, does not vary across vintages, $\mathcal{G}(u_{jt},m_{jt}) = \mathcal{G}(u_{j't},m_{j't}) \equiv \zeta_t$. (ii) If the function $\mathcal{G}(u,m)$ displays constant elasticity in the maintenance rate, maintenance expenses are proportional to the rental value of equipment services in all interior solutions of $u$ and $m$.*

Proposition 1 (i) implies that the utilization rate is a sufficient statistic for the physical depreciation rate and delivers a log-linear relationship between the price of equipment and the utilization rate. In equilibrium, the household adjusts the maintenance rate with the utilization rate to achieve an identical depreciation rate per unit of utilization across equipment stocks. This result follows from the assumption of constant elasticity in the utilization rate of $\mathcal{G}(u,m)$ and from the result that the equilibrium ratio of the rental rate to the price of equipment is identical across vintages.

The proportionality of maintenance expenses to the rental value of equipment services in Proposition 1 (ii) implies that we can write the per-period payoff, equation 10, as

$$\Psi_{jt} = r_{jt}u_{jt}\Lambda_t \quad \text{for} \;\; \Lambda_t \equiv \left(\frac{1-\zeta_t(\sigma_m+\sigma_u)}{1-\zeta_t\sigma_u}\right), \tag{11}$$

where $\sigma_u$ and $\sigma_m$ are the absolute value of the elasticities of the function $\mathcal{G}(u,m)$ with respect to the utilization and maintenance rates, respectively. The additional assumption of constant elasticity in the maintenance rate is sufficient for this result. Importantly, this assumption yields a verifiable implication for maintenance expenses, which are unobservable in our dataset. Empirical studies have shown that, controlling for observable characteristics, cumulated maintenance expenses in tractors increase in cumulated hours of usage and that a linear or convex relation fits the data well (Morris, 1988). Along with Proposition 1 (i), the assumption of constant elasticity in the maintenance rate implies that maintenance expenses are an exponential function of the utilization rate: $p_{jt}m_{jt} = p_{jt}\zeta_t u_{jt}^{\frac{\sigma_u}{\sigma_m}}$.

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function that satisfies Assumption 2 is $\delta(u,m) = ue^{-\frac{m^{\sigma_m}}{u^{\sigma_u}}}$ for parameters, $\sigma_m, \sigma_u > 0$.

**Rental rate of equipment services.** In equilibrium, the rental rate of equipment services of vintage $j$, $r_{jt}$, is the product of the quality of the vintage, $q_j$, and the marginal product of an efficiency unit, $\eta_t$. To characterize the latter, it is useful to write the efficiency units of equipment as the product of the level of embodiment, $q_{\hat{j}}$, and the number of efficiency units in units of the level of embodiment, $\widetilde{\kappa}_t \equiv \int_{j\in A_t} \frac{q_j}{q_{\hat{j}}}\kappa_{jt}dj$ (hereafter, normalized efficiency units). Then:

$$\eta_t \equiv \alpha_k \left(\frac{1}{q_{\hat{j}_t}}\right)^{1-\alpha_k} \left(\frac{\tilde{\kappa}_t}{\Phi_t}\right)^{\alpha_k-1} L^{\alpha_l} N^{\alpha_n}, \tag{12}$$

where $\frac{\tilde{\kappa}_t}{\Phi_t}$ is detrended normalized efficiency units of equipment. The equation above shows that to be able to measure $\eta_t$ we need a value for $\frac{\tilde{\kappa}_t}{\Phi_t}$. We characterize $\frac{\tilde{\kappa}_t}{\Phi_t}$ along the balanced growth path of the economy.

**Definition:** *A balanced growth path (BGP) is a sequential competitive equilibrium wherein output, consumption, equipment prices, and the efficiency units of equipment grow at a constant rate.*

The complete characterization of the BGP is in Proposition 3, in the Appendix. Here, we only highlight that, along the BGP, the detrended normalized efficiency units of equipment are constant. Therefore, the marginal product of an efficiency unit, $\eta_t$, falls with the level of embodiment, $q_{\hat{j}}$ (equation 12).

**The price of a unit of equipment.** Impose BGP conditions on the Euler equation and the results from Proposition 1 to solve for the price of equipment of vintage $j$:

$$p_{jt} = \frac{q_j \eta_t u \Lambda}{1-\psi}, \quad \text{for: } \psi \equiv \frac{1-ue^{-\zeta}}{R(1+g_q)^{1-\alpha_k}}, \tag{13}$$

where $\psi$ is the endogenous discount factor. The utilization rate and the depreciation rate per unit of utilization are constant along the BGP, and so the per-period payoff of any vintage shares the trend of the marginal product of an efficiency unit (equation 11).[13]

Equation 13 is the building block of our identification strategy. It links the price of equipment of vintage $j$ to two vintage-specific characteristics — namely, the quality of the vintage and the utilization rate; and to two common components — namely, the physical depreciation rate per unit of utilization and the marginal product of an efficiency unit of equipment, which depends on the level of embodiment in the economy.

[13] The discount factor is defined implicitly because the endogenous utilization rate (which characterizes the physical depreciation rate) is a function of the discount rate. See the proof of Proposition 3 for details.

# 4 Age-price profiles and the quality of equipment

We now use the equilibrium characterization of equipment prices to construct the theoretical counterpart of the empirical age-price profile that we estimated in Section 2. We show how the coefficients of the empirical age-price profile are linked to the path of embodied technology in an economy under balanced growth. We use this link to infer the path of embodied technology and that of quality-adjusted equipment services in agriculture for 16 countries between 1990 and 2014.

## 4.1 The theoretical age-price profile

We use no-arbitrage arguments to characterize the cross-sectional variation in tractor prices within a country. Define $p^k_{jt}(\{u_s, m_s\}^t_{s=t-a})$ to be the price of a tractor of vintage $j$ at time $t$ with patterns of utilization and maintenance rates for each age, $\{u_s, m_s\}^t_{s=t-a}$. We map a unit of time in our model to a year in the data and the utilization rate of a tractor to the number of hours the tractor is used in a year.

Consider first how the prices of tractors that were never used or maintained vary across vintages. By construction, the price of a new tractor is that of one unit of equipment, $p^k_{jt}(\{0,0\}) = p_{jt}$. In equilibrium, $p_{jt}$ is linear in its quality and the relative price of two tractors of different vintages is simply the ratio of their qualities. The price of a tractor of vintage $j$ that was never used or maintained is

$$p^k_{jt}(\{0,0\}) = \frac{q_j}{q_{\hat{j}_t}} p^k_{\hat{j}t}(\{0,0\}). \tag{14}$$

Now consider how the prices of tractors of a given vintage vary with utilization and maintenance. In equilibrium, the physical depreciation rate is the product of the utilization rate and a constant depreciation rate per unit of utilization $e^{-\zeta}$ (Proposition 1). Hence, the equipment services embedded in a tractor with utilization and maintenance rates $\{u_s, m_s\}^t_{s=t-a}$ are

$$\prod_{s=t-a}^{t} \left(1 - u_s e^{-\zeta}\right) \approx \exp(-e^{-\zeta} h),$$

where $h$ is the total hours of usage since a tractor was built, $h \equiv \sum_{s=t-a}^{t} u_s$. In equilibrium, households trading tractors should be indifferent between the prices of tractors of the same vintage, once adjusted for the equipment services embedded in them:

$$p^k_{jt}(\{u_s, m_s\}^t_{s=t-a}) \approx \exp(-e^{-\zeta}h) p^k_{jt}(\{0, 0\}).$$

The previous two no-arbitrage arguments are the building blocks for our theoretical age-price profile in equation 15.

**Proposition 2** (Theoretical age-price profile)**.** *Assume all tractors introduced in a country in a year are of the highest vintage that farms can operate. Along the balanced growth path, the price of a tractor of vintage $j$ with patterns of utilization and maintenance rates for each age $a$, $\{u_s, m_s\}^t_{s=t-a}$, at time $t$ satisfies*

$$\ln\left(p^k_{jt}(\{u_s, m_s\}^t_{s=t-a})\right) \approx -e^{-\zeta}h - \ln(1 + g_q)a + \ln\left(p^k_{\hat{j}_t t}(\{0, 0\})\right). \tag{15}$$

Three features are important to highlight. First, the coefficient on age identifies the growth rate of embodiment. The assumption that all *new* tractors are of the same vintage ensures that age is a sufficient statistic for the quality gap between the highest vintage in the market when the tractor was built and the current one. If we instead allow for a non-degenerate vintage distribution of new tractors, the theoretical age-price profile includes an additional quality gap between the vintage of the tractor being priced and the highest vintage in its cohort. This additional term is a cohort effect, which adds to the time and age effects already present in the theoretical age-price profile. A sufficient restriction on the cohort effect that ensures the empirical applicability of the profile is that the distribution of tractors' quality relative to the highest in the cohort has an identical mean across all cohorts (see Appendix B).[14]

Second, the variation in hours of usage per year across tractors identifies the hourly physical depreciation rate. This variation is rationalizable in the model by thinking that the household chooses the *average* utilization rate across all equipment units of a vintage and that, although all farms demand the same level of equipment services of a vintage, these services can be generated using each unit of equipment at different rates. This is consistent with the optimality conditions of the household because it adjusts utilization and maintenance rates so that physical depreciation per unit of utilization is identical across equipment units.

[14] Note that the equilibrium characterization of our model is silent with regards to the vintage composition of new equipment because the return and costs to investing in equipment are linear in the equipment's vintage quality. Without restrictions on the vintage distribution of new tractors, time effects enter into equation 15 in terms of the price of a new tractor of the best vintage, $p^k_{\hat{j}_t t}(\{0, 0\})$, whereas cohort effects enter in terms of the quality of the tractor being priced relative to the best vintage in its cohort, $\frac{q_j}{q_{\hat{j}_{t-a}}}$.

The maintenance expenses associated to this adjustment scale proportionally with utilization when the elasticities of the function $\mathcal{G}(u, m)$ with respect to utilization and maintenance rates are identical. We assume $\sigma_u = \sigma_m$ in the measurement.[15]

Third, the intercept of the theoretical age-price profile is the logarithm of the price of a new tractor in the market (in units of consumption). It is a function of the level of technology, $q_{\hat{j}}$, and other observables:

$$\ln\left(p^k_{\hat{j}_t t}(\{0,0\})\right) = \alpha_k \ln\left(q_{\hat{j}_t}\right) + \ln\left(\frac{R(1+g_q)^{1-\alpha_k} - \left(1 - ue^{-\zeta}\right)}{1-\psi}\right). \tag{16}$$

## 4.2 The path of quality-adjusted equipment services

To start, we postulate the sources of cross-country heterogeneity. Countries exogenously differ in their labor and land endowments (i.e., $N$ and $L$), in their shape of the physical depreciation function (i.e., $\sigma_m = \sigma_u$), in their shape of the adoption cost function (i.e., $\theta$ and $\omega$), and in their TFP in farming (i.e., $\Phi_t$). As a result, countries endogenously differ in their path of embodied technology, in their equipment services in farming, in their hours of usage and maintenance expenses for equipment, in their physical depreciation rates per unit of utilization, and in their aggregate output.

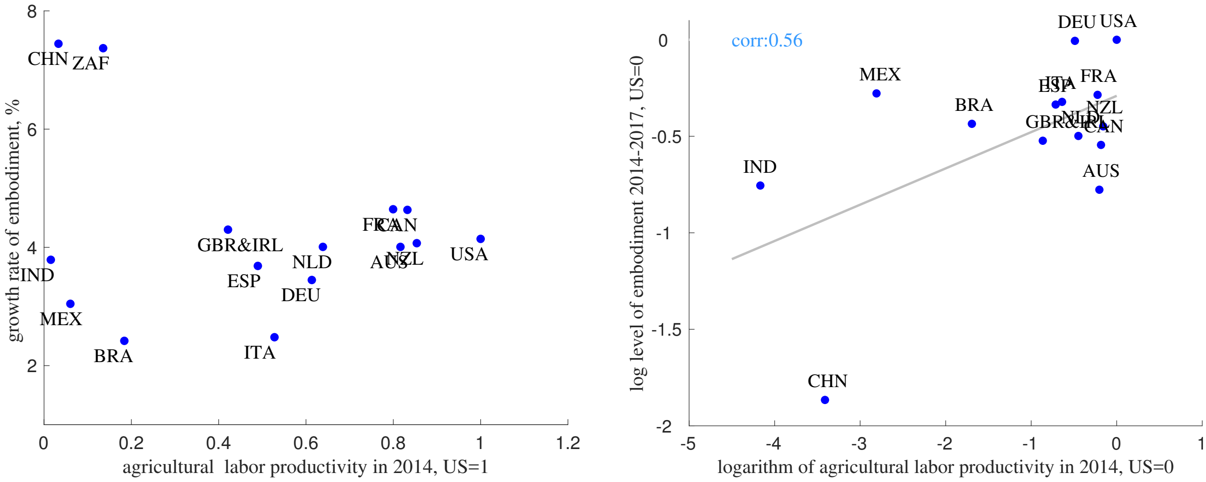
The mapping between the empirical age-price profile estimated in equation 1 (Section 2) and its theoretical counterpart in equation 15 is as follows:

$$\underbrace{\ln(p^k_{jit}(\{u_s, m_s\}^t_{s=t-a})p^c_{it})}_{p^e_{oit}} \approx \underbrace{-e^{-\zeta_i}}_{\gamma_{3i}} h \underbrace{-\ln(1+g_{iq})}_{\gamma_{2i}} a + \underbrace{\ln(p^k_{i\hat{j}_t t}(\{0,0\})p^c_{it})}_{\gamma_{1it}} + Controls,$$

where $i$ indexes countries, $p^c$ is the price of agricultural consumption goods (normalized to 1 in our model), and $\gamma_{1it}, \gamma_{2i}, \gamma_{3i}$ refer to the coefficients of the empirical profile. We include $Controls$ for tractors' HP and manufacturer as in equation 1. We exploit the assumption that, although quality is unobservable, a mapping to observable characteristics exists (as in Manuelli and Seshadri, 2014), and we use information on observable equipment characteristics to control for the average gap in the quality between each tractor and the highest quality in its cohort.

We use the link between the empirical and theoretical age-price profile to measure cross-

[15] The assumption of identical elasticities implies a proportional relation between maintenance expenses and hours of usage, controlling for equipment characteristics, which empirical studies show to fit the data well as documented in Morris (1988).




(a) growth (b) level

Figure III: Inferred path of embodied technology.

The figure shows the inferred path of embodied technology for the countries in our sample by plotting its growth rate and the logarithm of its level (adjusted by the equipment share in farming) relative to the United States as an average for the period 2014-2017. *Corr* refers to the correlation between the plotted variables. Source: Our own computations based tractors' catalogue prices.

country differences in quality-adjusted equipment services, or efficiency units of equipment. These differences stem from the path of embodied technology — that is, its growth rate $g_q$ and its level $q_{\hat{j}}$ — as well as from the level of normalized efficiency units $\widetilde{\kappa}$. We infer each of these three variables separately. Here we describe the key steps of the inference and defer the details to Appendix D.

**Growth rate of embodiment.** The coefficient on age for country $i$ in regression equation 1, $\gamma_{2i}$, measures the growth rate of embodiment in the country, $g_{iq}$. The average growth rate of embodiment in our sample is 4.2%. The United States, Great Britain, and Ireland measure growth rates of embodiment of such a magnitude. China and South Africa measure exceptionally high rates, of about 7%. On the opposite end, embodied technology in Italy, Brazil, and Mexico grew at a rate of 3% or below. Figure III panel (a) plots the growth rate of embodiment against agricultural labor productivity. If we exclude China and South Africa, the two countries with exceptionally high growth rates of embodiment, the growth rate of embodiment is positively correlated with the agricultural labor productivity.

**Level of embodiment in 2014-2017.** We use the country-specific intercepts in regression equation 1, $\gamma_{1i}$, to infer cross-country differences in the level of embodiment. The difference in the intercepts between two countries is the log difference in the price of their new tractors. This price can be written as the product between the price of capital relative to consumption, $p^k_{jit}(\{u_s, m_s\}^t_{s=t-a})$, and the price of consumption, $p^c_{it}$. We measure the latter in the data and use equation 16 to isolate cross-country differences in the level of embodiment, $q_{\hat{j}t}$, from the prices of the new tractors relative to consumption. For this, we need information on annualized physical depreciation rate.

We measure the annualized physical depreciation rate, $u_i e^{-\zeta_i}$, from the coefficient on hours of usage in the regression equation 1 — that is, $\gamma_{3i}$, and the average hours of usage in a country, computed from our dataset (see Table III). The sample average is 0.98% and richer countries have higher physical depreciation rates. The US rate is 0.75% compared with 0.21% in China (the smallest) and 2.4% in Germany (the highest). Figure VII plots the annualized depreciation rate against agricultural labor productivity and shows a positive correlation between the two variables, at 0.48. The correlation is even stronger when we consider hourly depreciation rates (at 0.72). Through the lens of our model, this latter evidence suggests that, on average, poor countries maintain their equipment more than rich countries per hour of usage.[16]

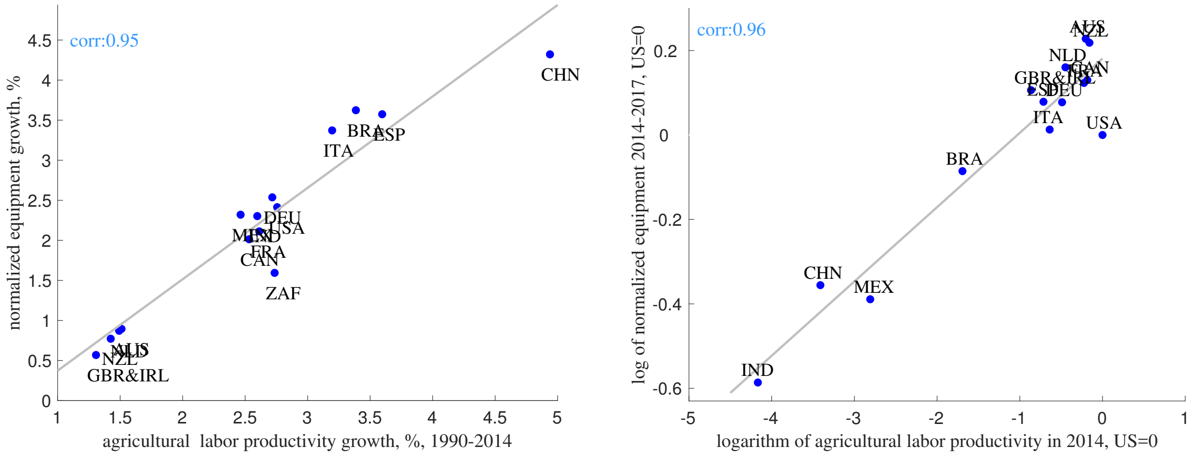
Figure III panel (b) plots the level of embodiment (adjusted by the equipment share in production) across countries relative to the United States, as an average for the 2014-2017 period. We measure a positive correlation between agricultural labor productivity and the level of embodiment across countries. For example, the best quality of agricultural equipment in the United States is 1.5 times larger than in Brazil, 2 times larger than in India, and 6.5 times larger than in China.

**Normalized efficiency units of equipment.** To measure cross-country differences in normalized efficiency units at a point in time, we use the specification of aggregate output in farming, which links the level of normalized efficiency units, $\widetilde{\kappa}_{it}$, to the level of detrended efficiency units, $\frac{\widetilde{\kappa}_{it}}{\Phi_{it}}$, and data on labor productivity, $\frac{Y_{it}}{N_i}$, and endowments, $N_i$ and $L_i$:

$$\frac{Y_{it}}{N_i} = \frac{\Phi_{it}}{\widetilde{\kappa}_{it}} \widetilde{\kappa}_{it} \frac{1}{N_i^{1-\alpha_k-\alpha_n-\alpha_l}} \left( q_{\hat{j}it} \frac{\widetilde{\kappa}_{it}}{\Phi_{it}} \frac{1}{N_i} \right)^{\alpha_k} \left( \frac{L_i}{N_i} \right)^{\alpha_l}.$$

We back out cross-country differences in detrended efficiency units from the specification of the marginal product of an efficiency unit of equipment, $\eta_t$, along the BGP. Last, the growth

[16] The magnitude of the annualized depreciation rates is in line with previous studies that recover them from data on usage (Perry et al., 1990). The Bureau of Economic Analysis sets the depreciation rate for farm tractors at 14.5%. One of the differences between the two sets of estimates is that our measure of depreciation does not include economic obsolescence (Cummins and Violante, 2002). If we were to add economic obsolescence (age effects in regression equation 1), our depreciation rates would average 5.2% across the countries in our sample (4.9% in the United States).




(a) growth (b) level

Figure IV: Inferred path of per-worker normalized efficiency units of equipment.
The figure shows the inferred path of per-worker normalized efficiency units of equipment for the countries in our sample by plotting its growth rate and the logarithm of its level (adjusted by the equipment share in farming) relative to the United States as an average for the period 2014-2017. *Corr* refers to the correlation between the plotted variables. Source: Our own computations based on tractors' catalogue prices.

rate of normalized efficiency units of equipment along the BGP is the growth rate of TFP (see Appendix C).

Figure IV plots the growth rate and level of normalized efficiency units per worker across countries. We find a strong positive correlation between the growth rate of labor productivity and that of normalized efficiency units, as well as a smaller dispersion in the level of normalized efficiency units compared with the level of embodiment.

# 5 Equipment quality and agricultural productivity

We assess the role of quality-adjusted equipment services in explaining labor productivity via income and growth accounting exercises.

**Development accounting.** We follow Caselli (2005) and start by measuring the success of our model in explaining cross-country agricultural productivity differences. This amounts to asking the following question: Suppose all countries had the same level of TFP; how would the distribution of agricultural labor productivity look compared to the actual distribution? We compute the proportion of the observed variance of log agricultural labor productivity,

$\ln\left(\frac{Y_{it}}{N_i}^d\right)$, captured by our model's predictions, $\ln\left(\frac{Y_{it}}{N_i}\right)$:

$$var\left(\ln\left(\frac{Y_{i2011-2014}}{N_i}\right)\right)/var\left(\ln\left(\frac{Y_{i2011-2014}}{N_i}^d\right)\right).$$

Our model explains 50% of the cross-country variation in agricultural labor productivity. What is the contribution of quality-adjusted equipment services? To answer this question, we compute how the explanatory power of our model would change if we were *not* to adjust for cross-country differences in quality-adjusted equipment services. If we set $\frac{\tilde{\kappa}_{it}}{N_{it}}q_{i\hat{j}} = \frac{\tilde{\kappa}_{USt}}{N_{USt}}q_{US\hat{j}}$ in each country, the model's explanatory power decreases to 13%. We conclude that quality-adjusted equipment services account for 37% of the cross-country variation in agricultural labor productivity in our sample.

To assess the quantitative importance of the quality adjustment to equipment services for agricultural productivity differences, we create a comparison benchmark using USDA-ERS data on the (HP-equivalent) number of tractors used in production. We take these numbers as a measure of the stock of tractor services not adjusted for quality. We find that the share of cross-country labor productivity differences accounted for by quality-adjusted equipment stocks is 1.8 times larger than without quality adjustment. Equipment services account for 16 pp more of the cross-country log-variance in agricultural labor productivity when stocks are quality-adjusted. The reason is that with quality adjustment, the cross-country differences in the stock of tractor services are larger than without quality adjustment; the log-variance increases from 2.7 to 9.0. Poor countries have relatively more tractors of lower quality than richer countries (see Figure VIII, panel (a), in Appendix E).[17]

Alternatively, we consider the measure of equipment stocks by Larson et al. (2000), which is commonly used in cross-country analyses of agricultural labor productivity. These data are available for 9 out of the 16 countries for which we constructed measures of quality-adjusted equipment services.[18] Our measures correlate at 0.81 with those of Larson et al. (2000), but our quality-adjusted equipment services are consistently lower than measured stocks in richer economies (the average difference from the United States is -42% in our data

[17] The proportion of the observed variance of log agricultural labor productivity captured by our model when equipment services are not quality adjusted is 34%, compared with 50% when the adjustment is applied. By means of a thought experiment equivalent to the income accounting exercise above, disparities in the quality of the average tractor (the ratio of our quality-adjusted stock of tractor services to the HP-equivalent number of operated tractors) account for 21% of the cross-country labor productivity differences.

[18] These countries are Australia, Canada, France, Great Britain, Ireland, India, Italy, the Netherlands, New Zealand, and the United States. Note that we are not able to identify the level of quality-adjusted equipment services for South Africa because we do not have data on average farm size for this country.

Table I: Development accounting exercise.

| agricultural value added relative to US: | | % explained by: Level of embodiment | Normalized eff. units | Land | Workers per farm | Total |
|---|---|---|---|---|---|---|
| Brazil | 18.6 | 25.9 | 5.1 | 46.1 | 13.3 | 90.3 |
| China | 3.2 | 54.3 | 10.3 | 39.8 | -6.3 | 98.1 |
| India | 1.6 | 18.3 | 14.2 | 30.9 | -1.8 | 61.7 |
| Mexico | 6.1 | 9.9 | 13.9 | 33.2 | 9.5 | 66.6 |
| Average | | 27.1 | 10.9 | 37.5 | 3.7 | 79.2 |

The first column reports the cross-country differences in agricultural labor productivity with respect to the United States between 2011 and 2014. The remaining columns report the percentage contribution to cross-country productivity differences of: the level of embodiment $q_{\hat{j}}$, normalized efficiency units per worker $\frac{\tilde{\kappa}}{N}$, land per worker $\frac{L}{N}$, and workers per farm $N$. Results are reported for countries in the bottom quartile of the agricultural income distribution. Factor shares and land endowments are imputed from the data as 2011–2014 averages.

compared with -16% in theirs); see Figure VIII, panel (b), in Appendix E. Quality-adjusted equipment services at the top of the labor productivity distribution vary more than Larson et al. (2000)'s measures.

The quantitative relevance of quality-adjusted equipment services for labor productivity differences requires a closer look into its two components: the level of embodiment and normalized efficiency units. Equalizing the level of embodiment across countries reduces the model fit to 25%, whereas equalizing normalized efficiency units reduces the model fit to 33%. Hence, differences in the level of embodiment account for 25% of the labor productivity differences, whereas differences in normalized efficiency units account for 17% of them.

Last, we use the specification of agricultural labor productivity in the model to decompose the difference in labor productivity in a given country with respect to the US into its components. Across the countries in our sample, quality-adjusted equipment services and land are the most important drivers of differences in agricultural labor productivity with respect to the US, on average. This is shown in Table I for the countries in the bottom quartile of the agricultural labor productivity distribution in our sample. The level of embodiment accounts for between 10% and 54% of the differences in agricultural labor productivities with respect to teh US, and the land endowment accounts for between 31% and 46%.

**Growth accounting.** We examine the role of the growth rate of embodiment for agricultural productivity growth over the past 25 years via a growth accounting exercise along the lines of Solow (1957) and Jorgenson and Griliches (1967). In balanced growth, the growth rate ($g$) of agricultural labor productivity relates to the path of quality-adjusted equipment services:

$$g^d_{\frac{Y}{N}i} = (1-\alpha_k)\mu_{\Phi_i} + \underbrace{\alpha_k g_{\frac{\tilde{K}}{N}i} + \alpha_k g_{qi}}_{\text{quality-adjusted equipment services}} + (1-\alpha_N-\alpha_k) g_{\frac{L}{N}i}, \qquad (17)$$

where the left-hand side is the growth rate of agricultural labor productivity in the data ($d$). Table II, column (1) reports this growth rate for the period 1990-2014, for the countries in our sample. The contribution of quality-adjusted equipment services can be split into the contribution of the growth of normalized efficiency units and the growth rate of embodiment. We show these two contributions in columns (2) and (3) of Table II, respectively. Finally, the last term in equation 17 represents the contribution of land per worker (assumed constant in the model) and its contribution is shown in column (4) of Table II.[19]

On average, in each country, the path of quality-adjusted equipment services explains 40% of the growth rate of labor productivity in agriculture between 1990 and 2014. At the extreme ends, the lowest contribution for labor productivity growth is recorded in Brazil and Italy at about 24%, whereas the highest one is recorded in Australia at 66%. Among economies with agricultural labor productivity below one-third of the US levels, the average contribution is about 40%. South Africa is an exceptional case, where such a contribution reaches 50%.

Of the total contribution of quality-adjusted equipment services, one can isolate the contribution of upgrades in the level of embodiment from that of increasing the normalized efficiency units. Quantitatively, the former is the most important component and accounts for 27.7% of labor productivity growth, on average, across countries. This finding carries an important implication. If we were not to account for upgrades in embodied technology, we would attribute 64.2% of observed growth in labor productivity to TFP instead of 36.5%, on average, across the countries in our sample. The contribution of tractor services for the growth in labor productivity rises from 11.9% without quality-adjustment to 39.7% with quality-adjustment.[20]

[19]The contribution of land per worker embeds the contribution of workers per farm (also assumed constant in the model). Workers per farm can be expressed as the ratio of average land per farm and average land per worker. For most of the countries in our sample, no significant variations in land per farm are observed between 1990 and 2001 (see Adamopoulos and Restuccia, 2014). Hence, workers per farm move over time proportionally with land per worker.

[20]Similar conclusions follow if we look at the contribution of the average quality of tractors to labor productivity growth, which averages 27.7% across the countires in our sample. To compute the growth

Table II: Growth accounting exercise

| | % Growth in labor productivity | %explained by: Embodiment | Normalized eff. units | Land per worker |
|---|---|---|---|---|
| Australia | 1.5 | 54.0 | 12.1 | -2.9 |
| Brazil | 4.9 | 9.7 | 14.6 | 31.0 |
| Canada | 3.4 | 26.7 | 11.6 | 26.1 |
| China | 6.4 | 23.1 | 13.4 | 22.6 |
| Spain | 5.0 | 14.6 | 14.1 | 28.0 |
| France | 4.8 | 19.0 | 8.6 | 46.0 |
| Great Britain & Ireland | 1.9 | 45.7 | 6.0 | 29.8 |
| Germany | 4.8 | 14.2 | 10.5 | 43.4 |
| India | 2.3 | 32.2 | 19.6 | -11.6 |
| Italy | 5.0 | 9.8 | 13.3 | 36.1 |
| Mexico | 2.8 | 21.1 | 16.1 | 13.5 |
| The Netherlands | 2.8 | 28.4 | 6.2 | 46.6 |
| New Zealand | 1.5 | 53.0 | 10.1 | 6.2 |
| United States | 3.5 | 23.7 | 13.8 | 20.1 |
| South Africa | 3.6 | 27.8 | 11.9 | 23.9 |
| Average | 3.6 | 27.7 | 11.9 | 23.9 |

The first column reports the average growth rate of agricultural labor productivity for the 1990-2014 period. The remaining columns report the percentage contribution to the growth rate of agricultural labor productivity of the growth rate of embodiment, $\alpha_k g_{qi}$; the growth rate of normalized efficiency units, $\alpha_k g_{\frac{\tilde{K}}{N}i}$; and the growth rate of land per worker, $(1-\alpha_k-\alpha_n)g_{\frac{L}{N}i}$.

Last, we find that the growth rate of embodiment accounts for a lower fraction of agricultural labor productivity growth in poorer countries. This contribution averages 21.5% in countries with agricultural labor productivity below one-third of the one in the United States, compared with 35.3% in countries with labor productivity above two-thirds of the one in the United States.

# 6 Discussion

In this section, we assess the robustness of our identification strategy and findings to two relevant extensions to the model: (i) international trade in equipment and (ii) a frictional equipment-producing sector.

rate of the quality of the average tractor, we use USDA-ERS data on the growth rate of (HP-equivalent) number of tractors in production and subtract it from the growth rate of quality-adjusted equipment services (columns (2)+(3) in Table II).

## 6.1 International trade in equipment

Tractors are widely traded goods (Eaton and Kortum, 2001), and international trade opportunities influence equilibrium tractor prices. In this section, we discuss how these opportunities affect our identification strategy.

Consider an extension of our benchmark model where equipment can be traded internationally. For expositional simplicity, we consider the case where international trade is frictionless. Equipment services and the final consumption good are non tradable. Hence, households can purchase equipment from either domestic producers or producers abroad. Once households choose their equipment holdings, they rent services to the farms in the domestic economy, and they consume goods produced by domestic farms.

Because equipment is traded internationally in frictionless markets, the price of any equipment vintage is equalized across countries. The price of equipment of vintage $j$, $p^I_{jt}$, is the product of its quality and the price of a unit of quality. We take the price of a unit of quality to be the numeraire and normalize it to 1, that is, $p^I_{jt} = q_j p^I_t = q_j$. The linear technology for transforming the consumption good into equipment implies that the price of consumption equals the relative productivity of the equipment-producing sector and the farming sector in each country, $p^C_{it} = q^{1-\alpha_k}_{i\hat{j}t}$. As in Hsieh and Klenow (2007), the price of equipment of a vintage is the same in countries with different levels of embodiment, but the price of agricultural goods is higher in countries with higher levels of embodiment.

How do international trade opportunities influence our identification strategy? First, notice the price of a tractor is still linear in the quality of its vintage and scales with physical depreciation. Hence, the arguments developed in Section 4.1 imply the shape of the age-price profile is the same as in our benchmark, equation 15. Importantly, the coefficient on age still measures the growth rate of embodiment in the domestic economy. Cross-country heterogeneity in this coefficeint arises because the gap in quality between new and old goods is different across countries — that is, not all countries have the same growth rate of embodiment.

The one departure from our benchmark identification is in a broken link between the intercept of the age-price profile and the level of embodiment. As before, the intercept of the age-price profile corresponds to the log price of new equipment. If trade were frictionless, cross-country heterogeneity in the intercept could reflect only cross-country heterogeneity in the level of embodiment. However, trade is frictional and disparities in the intercept of the age-price profile also reflect disparities in the price per unit of quality and thus trade barriers and the production cost of the country of origin. Our inference on the level of embodiment is then cluttered.

To move forward, we document that home-trade shares of machinery and equipment, a category that includes agricultural tractors, are non negligible for all the countries in our dataset. Home-trade shares are, on average, 77% across the countries in our sample (see Table IX). The implication of this finding is that at least one equipment vintage is produced domestically. Then, the absence of arbitrage opportunities across vintages in the domestic market (equation 14 of Section 4.1) implies we can relate the price of any vintage to domestic production costs. In particular, if new equipment is imported, we can relate its price relative to consumption to domestic production costs, and then recover the level of embodiment following our benchmark procedure in Section 4.1. Therefore, our identification method still infers the level of embodiment from the intercept of the age-price profile.

## 6.2 Frictional equipment markets

Multiple studies document differences in the price of identical tradable goods across countries, in excess of trade barriers. Goldberg and Verboven (2001), for example, find sizable differences in quality-adjusted prices of cars across European countries. These price differences have been linked to heterogeneous demand elasticities (e.g., due to search costs, preferences, competitiveness) that generate differences in markups across countries.[21] Particularly problematic for our inference are markups that covary with income per worker (and so most probably with agricultural labor productivity). Alessandria and Kaboski (2011) find an elasticity of the price of tradable consumption to income per worker of 23%, whreas Simonovska (2015) finds an elasticity of the price of apparel products to income per worker of 18%. In this section, we estimate the covariation of markups in the market for tractors with agricultural labor productivity across countries and quantify its implications for our findings on the role of quality-adjusted equipment for agricultural labor productivity.

We remain agnostic regarding the source of heterogeneous markups across countries and extend our model to include an exogenous and country-specific wedge between the marginal cost of producing equipment and the market price of equipment relative to consumption. The equilibrium price of equipment relative to consumption still equals the present discounted value of its rental services net of maintenance expenses because equipment rental markets are frictionless. The price is linear in quality and, therefore, our benchmark identification

[21] Our focus is on long-term deviations from the law of one price and, hence, the focus on local market conditions. Sticky prices in local currencies have been found to be an additional source of short-term deviations from the law of one price.

still recovers the growth rate of embodiment from the slope of the age-price profile.

The identification of the level of embodiment is, instead, problematic. With a wedge that mediates the relationship between prices and the marginal cost of producing equipment, the Euler equation in balanced growth recovers only the ratio between the marginal product of an efficiency unit of equipment and the wedge. Then, under our benchmark identification, differences in the intercept of the age-price profile across countries are also a function of the wedge. To disentangle the level of embodiment, we measure the wedges in the markets for tractors and for consumption separately. We parameterize both wedges from international price differences between origin and destination countries of identical goods, in excess of measured trade barriers.

For tractors, we use a subset of our dataset for which we can trace the country of origin of the tractor transacted and construct a panel of tractor vintages across origin and destination countries. Our sample includes 12 countries (listed in Table X) and 3,660 vintages observed over varying years between 2007 and 2016. A vintage is defined by the model, manufacturer and year built, and disparities in prices from hours of usage and age are cleaned for.[22] We follow Simonovska (2015) and estimate

$$\ln\left(\frac{p^e_{ji'it}}{p^e_{ji'i't}}\right) = \gamma_{6ji'} + \gamma_7 \ln\left(\frac{y_i}{y_{i'}}\right) + \gamma_8 \text{Trade barriers} + \epsilon_{ji'it}. \tag{18}$$

where $p^e_{ji'it}$ is the price of a tractor of vintage $j$ sold in country $i'$ at time $t$ and produced in country $i$, while $y$ is agricultural labor productivity. We assume trade barriers depend on trading partners, geographical locations and trade policy attributes and add standard gravity variables to control for these barriers.[23] We include a vintage-destination effect, $\gamma_{6ji'}$. The error in the regression equation 18 is normally distributed, mean-zero, and i.i.d. across observations. Our parameter of interest is $\gamma_7$, which measures the elasticity of price disparities between source and destination country to disparities in agricultural labor productivity.

We estimate regression equation 18 by treating $\gamma_{6ji'}$ as random effects. Table X shows these results. The estimated coefficient on agricultural labor productivity varies between 6.7% and 7.9%, depending on the specification. These values are consistent with estimates

[22] An example of equipment vintage in our dataset is a model 8430 John Deere tractor built in 1970. We clean prices for age and hours effects using regression equation 1, and express all prices in new-good equivalents.

[23] We include a third-order polynomial of log distance between origin and destination country and a dummy variable that takes value 1 if origin and destination countries are in a trade agreement. Gravity variables are from Head et al. (2010).

of international pricing to market for capital goods and goods traded in organized exchanges (7% in Alessandria and Kaboski, 2011).

Equivalently, we consider international price differences in the tradable component of agricultural consumption, in excess of trade barriers. We use Alessandria and Kaboski (2011)'s estimates of the price elasticity of tradable consumption to income per worker to measure the price elasticity of overall consumption.

Finally, we combine our estimated price elasticity of tractor vintages to agricultural labor productivity with that of consumption to find an elasticity of the wedge to agricultural labor productivity of 8% - 23% = -15%. When we take into account cross-country heterogeneity in the wedge, the contribution of the level of embodiment to cross-country variation in labor productivity increases to 45% (20 pp above the benchmark) and the contribution of quality-adjusted equipment services increases to 54% (17 pp above the benchmark).

# 7 Conclusion

In this paper, we study the implications of embodied technology for agricultural productivity differences across countries. To do so, we construct a novel dataset of prices for second hand equipment (tractors) across countries at different stages of development and build a framework that maps these prices to the path of technology embodied in equipment.

We measure the role of embodied technology in agricultural labor productivity via standard growth and income accounting exercises. We conclude that accounting for quality almost doubles the importance of differences in capital stocks for differences in agricultural labor productivity across countries. The reason is that richer countries have capital of higher quality, on average. Additionally, the role of capital for labor productivity growth increases by a 3-fold when accounting for quality. The reason is that embodied technology has grown at an average annual rate of 4.2%, over the last 25 years.

Our findings suggest that a promising avenue for future research would be understanding of barriers to the diffusion of technology embodied in agricultural equipment. This effort may entail bridging together the development literature on micro-barriers to mechanization and structural macro-models of diffusion. The analysis of the characteristics of secondary markets for durable goods across countries, as well as the availability of market arrangements that may overcome barriers to mechanization related to economies of scale, is a natural focus of interest.

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# A Data construction and estimation

Our dataset consists of tractor prices, along with their characteristics. We impute hours of usage for those observations for which this information is missing and we delete all observations that are missing any other information. Detailed information on the construction of the dataset and comparisons to Census data can be found in the Online Appendix.

We complement our dataset with two additional sets of data that we use for robustness checks. First, using data from the EarthStat dataset constructed by Ramankutty et al. (2008), we search for the crop with the highest recorded yield produced in a 20-mile-wide grid around each sale location and match this information with our tractor price data. EarthStat consists of agricultural census and survey information on crop land areas and yields for 175 crops measured at the smallest political units reasonably obtainable for 206 countries. Available grid sizes are 5-arc min (which is roughly equivalent to an area of $10^2$ km). Further details, in particular on yields computations, are available in the Online Appendix. Second, we complement the main dataset with wages of repair workers in each country. We use the NBER "Occupational wages around the world" dataset, which provides occupational wage data for 161 occupations in 171 countries from 1983 to 2008 by calibrating observed wages into a normalized wage rate for each occupation. These two sets of controls, crop and wages, are available for a sub sample of our dataset that consists of more than 180,000 catalogue prices (see Figure VI).

We test the robustness of our baseline results presented in Section 2 for alternative data and empirical models. Table V compares the estimates for the slope of the age-price profile, $\gamma_{2i}$, that result form using our raw data (column (1)) and our main dataset (column (2)). In addition, the Online Appendix presents additional results for estimations that ignore data for the United States and Canada and for estimations that use transaction prices rather than catalogue prices.

Estimates for the alternative specifications of regression equation 1 discussed in Section 2 are in Tables VII and VIII. Columns (2) through (5) consider an extended regression equation that includes controls for the type of cultivated crops and the wages of repair workers. Wages are deflated using the purchasing power parity deflators from the Penn World Tables 7.0 and then interacted with hours of usage. Our benchmark results do not include these controls because estimates do not shift systematically across the development spectrum and the sample size is three times as large without controls. Column (6) of Tables VII and VIII generalizes the regression equation 1 to allow for an arbitrary shape of the decay of prices with age and hours of usage, away from the logarithmic profile. We impose a Box-Cox transform on the tractor price and estimate its shape coefficient. We find the profile is more convex than a logarithmic one, with an estimated shape parameter on the price equal to 0.13 (an estimate of 0 corresponds to a logarithmic profile). To compare the predictions of this specification with our benchmark, we report the price semi-elasticity to age for a synthetic tractor manufactured by John Deere and hours of usage, horsepower, and age equal to the median in the sample.

# B Age, cohort and time effects

The theoretical age-price profile in Proposition 2 relies on the assumption that all tractors introduced in an economy in a year are of the highest vintage that farms in the economy can operate. Under a fully flexible distribution of new tractors by vintage, the theoretical age-price profile is:

$$\ln\left(p^k_{jt}(\{u_s, m_s\}^t_{s=t-a})\right) = -e^{-\zeta_i} h - \ln(1+g_q)a + \ln\left(p^k_{\hat{j}_t t}(\{0,0\})\right) + \ln\left(\frac{q_j}{q_{\hat{j}_{t-a}}}\right).$$

The last term is a cohort effect and it adds to the time and age effects already present in our baseline theoretical age-price profile (equation 15). The three effects are collinear and the profile cannot be estimated as is. Here, we show that to overcome this challenge, a sufficient condition is that,

**Assumption 3.** *The average gap in quality between each equipment and the highest quality in its cohort is constant across cohorts; that is* $\frac{1}{C_{t-a}} \sum_{o \in \mathbf{C}_{t-a}} \frac{q_j(o)}{q_{\hat{j}_{t-a}}}$ *is constant in time* $t$*, where* $\mathbf{C}_{t-a}$ *is the set of equipment goods introduced at time* $t-a$ *and* $C_{t-a}$ *is the cardinality of this set.*

To understand the implications of Assumption 3 in a cross section of data, express the gap in quality between each equipment and the highest quality in its cohort ($q_{\hat{j}t-a}$) as

$$q_j = q_{\hat{j}t-a} \frac{q_j}{q_{\hat{j}t-a}} = q_{\hat{j}t-a} \frac{1}{(1+g_q)^{\nu_a}},$$

where $\nu_a$ describes the mapping between age and quality in the cross section. For example, if $\nu_a$ equals 0 for all $a$, we are imposing a one-to-one mapping between age and quality — that is, all equipment goods are of the quality that was highest in the year they were introduced. On a two-dimensional plane, with age on the horizontal axis and the logarithm of quality on the vertical axis, this mapping has intercept at $\ln(q_{\hat{j}t})$ and slope $-(1+g_q)$ (see Figure V, red-continuous line). This mapping is the one we assume in the derivation of the theoretical age-price profile in Proposition 2. We refer to this mapping as the baseline mapping.

Assume $\nu_a = \nu_1 + \nu_{2a}$, so that $\nu_1$ captures departures from the baseline mapping in the intercept (e.g., the blue-striped line in Figure V). To avoid collinearity among the cohort, time and age effects, $\nu_{2a}$ must be uncorrelated with age (e.g., the blue dots in Figure V). Assumption 3 ensures that this restriction is respected by imposing that across all cohorts the average tractors introduced is a constant number of $(1+g_q)$-size increments to the best one available in the market. In addition, note that systematic cross-country differences in $\nu_1$ induce a bias in our inference on the level of embodiment from the intercept of the age-price profile. To attenuate this bias, we include controls for equipment characteristics in the estimation of the empirical age-price profile.

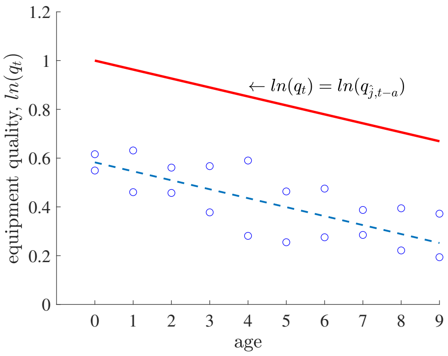



Figure V: Restriction on cohort effects.

Mapping between tractor quality and age in a cross-section of data. The red-continuous line is the quality of the best vintage introduced in each year $t-a$. The blue-striped line is the average quality of the average vintage introduced in each year $t-a$.

# C Equilibrium definition and proofs

**Definition:** An **allocation** consists of sequences of consumption, investment, usage, and maintenance rates in stocks of different vintages $\{c_t, x_{jt}, u_{jt}, m_{jt}\}_{t=0}^{\infty}$; sequences of embodied technology, equipment services, land, and labor demands by farms $\left\{q_{\hat{j}t}, \kappa_{jt}, l_t, n_t\right\}_{t=0}^{\infty}$; as well as sequences of investment goods $\{y_{jt}^x\}_{t=0}^{\infty}$.

**Definition:** A **sequential competitive equilibrium** is an allocation and sequences of prices $\{p_{jt}, r_{lt}, r_{jt}, w_t\}_{t=0}^{\infty}$ such that, given the law of motion of the world technology frontier, $q_J$, as well as adoption and production technologies, households maximize utility (equation 6 subject to equations 7 and 8), equipment-producing firms and farms maximize profits, (equations 9 and 5), and markets clear:

- Final consumption good: $c_t + x_t^q + \int_{j \in A_t} y_{jt}^x \frac{q_j}{q_{\hat{j}t}^{1-\alpha_k}} dj = Y_t = y_t$,
- Land: $l_t = L_t = L$,
- Labor: $n_t = N_t = N$,
- Equipment:
    1. The demand for equipment services from farms equalizes the supply from households,

       $\kappa_{jt} = u_{jt} k_{jt}$,
    2. The production of investment goods equals its demand,

       $y_{jt}^x = x_{jt} + k_{jt} m_{jt}$,
    3. The set of vintages used in production, $A_t$, equals the set of vintages held by the household, $A_t^h$.

*Proof.* *Proposition 1.* The optimality conditions for usage and maintenance, given the budget constraint of the household, are

$$e^{-\mathcal{G}(u_{jt},m_{jt})}(1-u\mathcal{G}_1(u_{jt},m_{jt}))=\frac{r_{jt}}{p_{jt}}, \tag{19}$$

$$u_{jt}e^{-\mathcal{G}(u_{jt},m_{jt})}\mathcal{G}_2(u_{jt},m_{jt})=1, \tag{20}$$

where $\mathcal{G}_v$ is the derivative of $\mathcal{G}(u,m)$ with respect to the $v$-th element.

Given the constant elasticity of $\mathcal{G}(u,m)$ with respect to usage, $\sigma_u \equiv |\frac{\mathcal{G}_1 u}{\mathcal{G}}|$, we can rewrite equation 19 as:

$$e^{-\mathcal{G}(u_{jt},m_{jt})}(1-\mathcal{G}(u_{jt},m_{jt})\sigma_u)=\frac{r_{jt}}{p_{jt}}. \tag{21}$$

Equation 21 returns a solution $\mathcal{G}(u_{jt},m_{jt}) \equiv \zeta_{jt}$. We focus on an interior solution with $\zeta_{jt} \in (0,\infty)$.[24]

The ratio $\frac{r_{jt}}{p_{jt}}$ is independent of the vintage. To show this, consider first the optimality condition of the equipment producing firms. These firms price at marginal cost and so the price of equipment equals $p_{jt}=q_j\frac{1}{q_{\hat{j}t}^{1-\alpha_k}}$ and is linear in quality. Then, consider the optimality condition of the farm with respect to equipment. The rental rate of equipment services equals the marginal product of an efficiency unit of equipment in farming times the quality of the vintage:

$$r_{jt}=q_j\alpha_k\Phi_t^{1-\alpha_k}\left(\int_{j\in A_t} q_j\kappa_{jt}dj\right)^{\alpha_k-1}L^{\alpha_l}N^{\alpha_n}. \tag{22}$$

Hence, $\frac{r_{jt}}{p_{jt}}$ is independent of the vintage. It follows that $\zeta_{jt}=\zeta_t\ \forall j$.

To show that maintenance expenses are proportional to the rental value of equipment services, assume the elasticity of the function $\mathcal{G}(u,m)$ with respect to the maintenance rate $m$ is constant, $\sigma_m \equiv |\frac{\mathcal{G}_2 m}{\mathcal{G}}|$. This assumption and the result $\mathcal{G}(u_{jt},m_{jt})=\zeta_t$ allow us to rewrite equation 20 as:

$$\frac{u_{jt}}{\mathrm{m}(u_{jt})}e^{-\zeta_t}\zeta_t\sigma_m=1, \tag{23}$$

where $\mathrm{m}(u):[0,1]\to[0,1]$ is a function implicitly defined by $\mathcal{G}(u_{jt},\mathrm{m}(u_{jt}))=\zeta_t$. The assumption of constant elasticities in $u$ and $m$ implies that $\mathrm{m}'(u)=\frac{\mathrm{m}(u)}{u}\frac{\sigma_u}{\sigma_m}$. Integrating on both sides of the previous equation and restricting maintenance to be positive, we obtain the functional form for $\mathrm{m}(u_{jt})$:

$$m_{jt}=\zeta_t u_{jt}^{\frac{\sigma_u}{\sigma_m}}. \tag{24}$$

Substituting this functional form in equation 23, we obtain the optimal utilization rate: $u=(e^{-\zeta_t}\sigma_m)^{\frac{\sigma_m}{\sigma_u-\sigma_m}}$ when $\sigma_m \neq \sigma_u$. The optimal utilization rate is identical across vintages as $e^{-\zeta_t}$ is identical across vintages. By equation 24, it follows that the maintenance rate is also independent of the vintage. A sufficient condition for an interior solution of the

[24] A sufficient condition for an interior solution is $\frac{r_{jt}}{p_{jt}} \leq 1$. We show that there exists parameters such that this condition is satisfied along the BGP (see the proof of Proposition 3).

utilization rate when $\sigma_u > \sigma_m$ is $\sigma_m \leq \frac{1}{e^{-\zeta_t}}$.

Finally, if $\sigma_m = \sigma_u$ the optimal utilization and maintenance rates are indeterminate and we find an interior solution for the depreciation rate per unit of utilization when $\sigma_m = \sigma_u = \frac{1}{e^{-\zeta_t}}$.

We take the ratio of equation 23 to equation 19 to obtain

$$\frac{r_{jt}u_{jt}}{p_{jt}m_{jt}} = \frac{(1-\zeta_t\sigma_u)}{\zeta_t\sigma_m},$$

which proves that maintenance expenses, $p_{jt}m_{jt}$, are proportional to the rental value of equipment services, $r_{jt}u_{jt}$.

□

**Remark** (Adoption of capital-embodied technology)**.** *Define a farm's level of embodiment relative to the world frontier as* $Z_t \equiv \frac{q_{\hat{j}t}^{1+\theta}}{(q_{J_{t-1}})^{\theta}(1+\theta)}$. *The equilibrium path of* $Z$ *satisfies:*

$$\omega = \frac{1+\mu_\Phi}{R_{t+1}}\left[\alpha_z\alpha_k\frac{q_{\hat{j}t+1}^{\alpha_k}}{Z_{t+1}}\left(\frac{\widetilde{\kappa}_{t+1}}{\Phi_{t+1}}\right)^{\alpha_k}L^{\alpha_l}N^{\alpha_n}\frac{\kappa_{\hat{j}t+1}}{\widetilde{\kappa}_{t+1}} + \frac{\omega}{(1+\mu)^{\frac{1-\alpha_z}{\alpha_z}}}\right]. \tag{25}$$

*Proof.* Solving the integral in the cost of adoption (equation 4) and using the law of motion of the world frontier (equation 26), we obtain the law of motion for $Z$:

$$Z_{t+1} = \frac{Z_t}{(1+\mu)^{\frac{1-\alpha_z}{\alpha_z}}} + \frac{x_t^q}{\omega\Phi_t}. \tag{26}$$

A farm's output can be written as

$$y = \Phi_t^{1-\alpha_k}z_t^{\alpha_k}(Z_t^{\alpha_z}\widetilde{\kappa}_t)^{\alpha_k}L^{\alpha_l}N^{\alpha_n}, \tag{27}$$

where $\alpha_z \equiv \frac{1}{(1+\theta)}$ and $z_t \equiv \frac{\left(q_{J_0}(1+\mu)^{t-1}\right)^{1-\alpha_z}}{\alpha_z^{\alpha_z}}$.

The optimal level of embodiment relative to the world frontier at each point in time, $Z_{t+1}$, follows from the optimality conditions of the farm when choosing its upgrade policy,

$$\omega\left(\frac{q_{\hat{j}t+1}}{Q_{jt}}\right)^{\theta} = \frac{1+\mu_\Phi}{R_{t+1}}\left[\alpha_k q_{\hat{j}t+1}^{\alpha_k-1}\left(\frac{\widetilde{\kappa}_{t+1}}{\Phi_{t+1}}\right)^{\alpha_k}\frac{\kappa_{\hat{j}t+1}}{\widetilde{\kappa}_{t+1}}L^{\alpha_l}N^{\alpha_n} + \omega\left(\frac{q_{\hat{j}t+1}}{Q_{jt+1}}\right)^{\theta}\right]. \tag{28}$$

Rewriting the above expression in terms of the quality gap to the frontier we obtain the result.

□

**Proposition 3** (BGP allocations)**.** *Along the BGP, the equipment utilization rate, u, the maintenance rate, m, and therefore the depreciation rate per unit of utilization,* $e^{-\zeta}$ *are constant; while normalized efficiency units,* $\tilde{\kappa}$*, grow proportionally to TFP. The growth rate of embodiment,* $g_q$*, is*

$$g_q = \frac{1-\alpha_z}{1-\alpha_k\alpha_z}\mu, \quad \textit{where: } \alpha_z \equiv \frac{1}{(1+\theta)} \leq \frac{1-(\alpha_l+\alpha_n+\alpha_k)}{\alpha_k}.$$

*Proof.* *Guess*: The depreciation rate per unit of utilization, $e^{-\zeta}$, is constant along the balanced growth path.

Under our guess, the depreciation rate per unit of utilization, $e^{-\zeta}$, is constant over time. Equation 21 then implies that the ratio $\frac{r_{jt}}{p_{jt}}$ is constant over time. Hence, the growth rate of the equipment price $p_{jt}$, $g_{p_j}$, equals that of its rental rate, $g_{r_j}$. To derive $g_{r_j}$, we rewrite the optimality condition of the farm in equation 22 as a function of normalized efficiency units, $\tilde{\kappa}$, and the level of embodiment $q_{\hat{j}}$:

$$r_{jt} = \left(\frac{\widetilde{\kappa}_t}{\Phi_t}\right)^{\alpha_k - 1} \frac{q_j}{q_{\hat{j}t}^{1-\alpha_k}} \alpha_k N^{\alpha_n} L^{\alpha_l}.$$

Then:

$$g_{r_{jt}} = (\alpha_k - 1)(g_{\tilde{\kappa}} - \mu_\Phi) + (\alpha_k - 1) g_q.$$

When we focus on the rental rate of the vintage that embodies the level of technology, $\hat{j}$, the previous equation modifies to be:

$$g_{r_{\hat{j}}} = (\alpha_k - 1)(g_{\tilde{\kappa}} - \mu_\Phi) + \alpha_k g_q.$$

Then, consider the optimality condition of the equipment producing firms, $p_{jt} = \frac{q_j}{q_{\hat{j}t}^{1-\alpha_k}}$. This condition implies that the price of the vintage that embodies the level of technology grows at rate $g_{p_{\hat{j}}}$:

$$g_{p_{\hat{j}}} = \alpha_k g_q. \tag{29}$$

Then, $g_{r_{\hat{j}}} = g_{p_{\hat{j}}}$ implies that the normalized efficiency units grow proportional to TFP:

$$g_{\tilde{\kappa}} = \mu_\Phi.$$

Therefore,

$$g_{r_{jt}} = (\alpha_k - 1) g_q.$$

Under our guess of a constant depreciation rate per unit of utilization, equations 23 and 24 imply that the utilization and maintenance rates are constant along the BGP. In addition, result (ii) in Proposition 1 and equation 12 imply that maintenance expenses are a fixed proportion of the rental value of equipment services. The Euler equation can then be solved recursively to describe equipment prices as the present discounted value of the payoff to equipment:

$$p_{jt} = \frac{r_{jt} u \Lambda}{1 - \psi(u, m, g_q)}, \quad \text{for a discount factor: } \psi(u, m, g_q) \equiv \frac{\left(1 - u e^{-\zeta}\right)}{R(1 + g_q)^{1-\alpha_k}}.$$

Using equation 19 we can solve for $\zeta$ implicitly. Note that the ratio of the rental rate of equipment services to the price is only a function of time-invariant parameters, $\frac{r_{jt}}{p_{jt}} = \frac{1-\psi(u,m,g_q)}{u\Lambda}$, and so a constant over time. Hence, it must also be true that $\zeta_t = \zeta \ \forall t$. This confirms our guess of constant depreciation rate per unit of utilization, $e^{-\zeta}$.[25]

Then, impose BGP conditions on the Euler equation to obtain:

$$1 = \frac{1}{R}\frac{1}{(1+g_q)^{1-\alpha_k}}\left[\Lambda u\left(\frac{\widetilde{\kappa}_{t+1}}{\Phi_{t+1}}\right)^{\alpha_k-1} L^{\alpha_l}N^{\alpha_n}\alpha_k + 1 - ue^{-\zeta}\right]. \tag{30}$$

The above equation pins down the marginal product of an efficiency unit of equipmnet:

$$\eta_t = \frac{R(1+g_q)^{1-\alpha_k} - \left(1 - ue^{-\zeta}\right)}{u\Lambda}\left(\frac{1}{q_{\hat{j}t}}\right)^{1-\alpha_k}. \tag{31}$$

Replace the equilibrium price of equipment (equation 9) and the rental rates of labor and land in the budget constraint of the household (equation 8). Define normalized efficiency units of investment to be $\widetilde{x}_t \equiv \int_{j\in A_t}\frac{q_j}{q_{\hat{j}}}u_{jt}x_{jt}dj$. Note that these grow at the same rate as the efficiency units of equipment $\tilde{\kappa}_t$ as the depreciation rate is constant along the BGP, $g_{\widetilde{x}} = g_{\widetilde{\kappa}} = \mu_\Phi$ (see the law of motion for equipment in equation 7). Imposing BGP conditions on the budget constraint of the household modified as described above, we conclude that consumption grows at the same rate as output in the farming sector, $g_y = g_c = \alpha_k g_q + \mu_\Phi$

Last, we characterize the equilibrium growth rate of embodiment, $g_q$. The definition of $Z$ relates its growth rate to that of embodiment, $g_q = (\alpha_z g_Z + (1-\alpha_z)\mu)$. The optimality conditions describing the level of embodiment relative to the world frontier, $Z$ (equation 25), require that in balanced growth $Z$ grows proportionally to the growth rate of embodiment, $g_Z = \alpha_k g_q$. Replacing this equilibrium condition, we obtain

$$g_q = \frac{1-\alpha_z}{1-\alpha_k\alpha_z}\mu.$$

Along the BGP, the growth rate of embodiment is increasing in the share of equipment in farming production. A constraint on factor shares and the elasticity of the cost function with respect to embodied technology, $\theta$, assures that while capital services grow, the optimal size of a farm is still pinned down: $\alpha_z \equiv \frac{1}{(1+\theta)} \leq \frac{1-(\alpha_l+\alpha_n+\alpha_k)}{\alpha_k}$,

□

*Proof. Proposition 2.* The proof follows from the two no-arbitrage arguments made in the main text, Proposition 1 and the characterization of the BGP. Combining them, we describe the price of a tractor of an arbitrary vintage and with arbitrary patterns of utilization and maintenance as a function of the price of a new tractor which embodied the current level of embodiment:

$$p^k_{jt}(\{u_s, m_s\}^t_{s=t-a}) = \exp(-e^{-\zeta}h)\frac{q_j}{q_{\hat{j}t}}p^k_{\hat{j}t}\left(\{0,0\}\right). \tag{32}$$

[25] A solution to equation 19 exists if $\frac{r_{jt}}{p_{jt}} \leq 1$. When $\sigma_u > 1$ and $\sigma_m > 1$, $\Lambda > 1$. Then, $\frac{r_{jt}}{p_{jt}} \leq 1$ when the utilization rate equals $u = 1$. By continuity, there exist $\sigma_m$ and $\sigma_u$ such that $\frac{r_{jt}}{p_{jt}} \leq 1$ when the utilization rate is close to 1.

Under the assumption that only one vintage is introduced in the market in each period, $q_j$ corresponds to the best vintage traded in the market $a$-years ago, that is, $q_j = q_{\hat{j}_{t-a}}$. Then, applying logs to equation 32, we obtain the result.

□

# D Details on the inference of the path of quality-adjusted equipment services

We measure cross-country differences in the price of consumption using purchasing power parity prices for food and nonalcoholic beverages in the 2011 International Comparison Program dataset. We normalize the price of agricultural consumption to be 1 in the United States. The price of agricultural consumption is 47% that of the United States in India, and 79% to 77% in Mexico and China.

We use the U.S. Department of Agriculture Economic Research Service (USDA-ERS) dataset published in relation to the study by Fuglie (2015) for information on factor shares. The labor, land, and equipment shares are set at US values and are 33.0%, 30.6%, and 19.7%, respectively.[26] We also use the USDA-ERS dataset for information on agricultural labor productivity. Agricultural labor productivity is the product of the value of gross agricultural production and 1 minus the sum of intermediate input factor shares, as published by the USDA-ERS.

To measure labor and land endowments per farm, we combine the information on agricultural land and labor published by the USDA-ERS with the information on average plot size collected by Adamopoulos and Restuccia (2014). Assuming equal land to labor ratios across farms, we construct a measure of the average employment per farm, $N_i$, which is the unit of production in the model.

We measure the growth rate of TFP, $\mu_{i\Phi}$, residually from agricultural labor productivity growth, given the growth rate of embodiment: $g_{i\frac{Y}{N}} = \alpha_k g_{iq} + \mu_{i\Phi}$.

Along the balanced growth path, the interest rate is the product between the inverse of the preference discount factor $\beta$ and the gross growth rate of aggregate output as described by the growth rate of embodiment and the growth rate of TFP. We set $\beta$ to 0.95.

Combining the interest rate, the annualized depreciation rate, and the growth rate of embodiment we measure the discount factor using equation 13.

Last, to measure the marginal product of an efficiency unit of equipment, $\eta$, we use its definition in equation 12 and its level in balanced growth in equation 31. We set the elasticity of utilization and maintenance rates to assure an interior solution for the depreciation rate per unit of utilization $\sigma_{mi} = \sigma_{ui} = \frac{1}{e^{-\varsigma_i}}$ (see the proof of Proposition 1).

[26]Because our focus is on labor productivity, we disregard intermediate input shares, which include crops materials (fertilizers, pesticides, seeds), and animal materials (pharmaceutical, feeds).

# E Figures and Tables

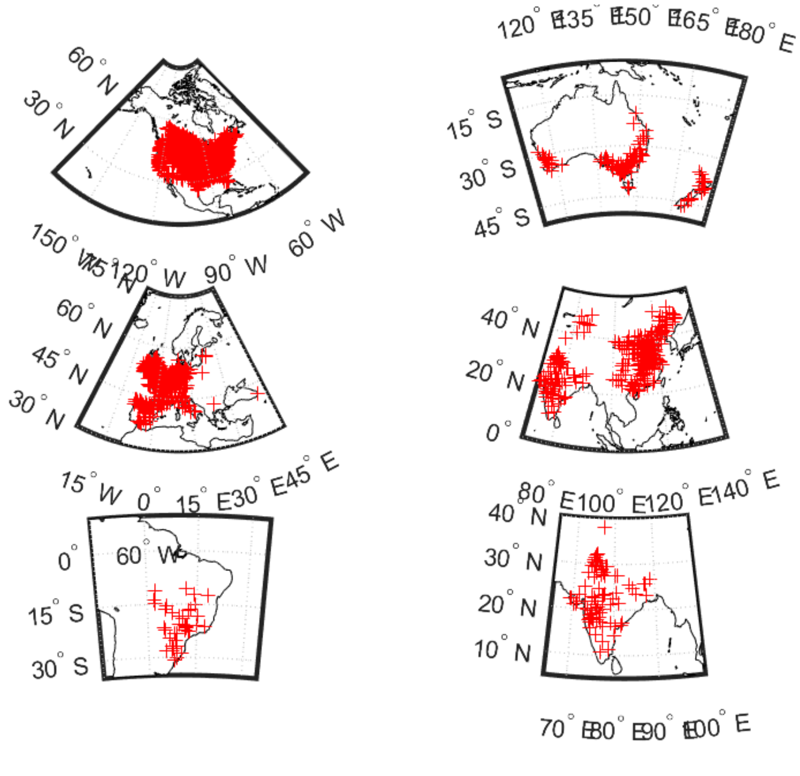


Figure VI: Matched Dataset in Space.
Geographical distribution of catalogue tractor prices matched via geolocation (120,374 observations).

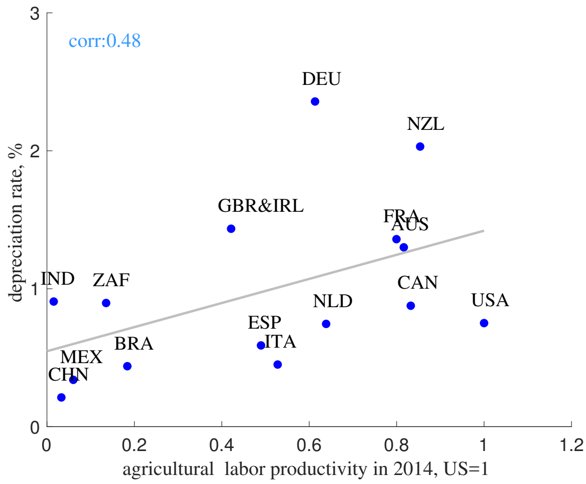
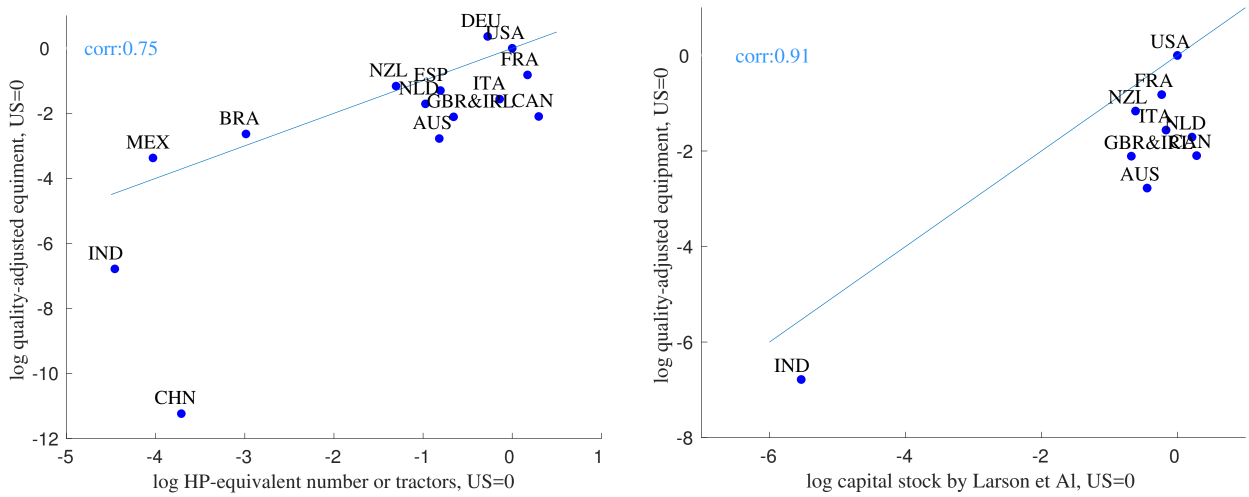



Figure VII: Annual Depreciation Rates. Inferred annualized depreciation rates, $u_i e^{-\zeta_i}$, for the countries in our sample. *Corr* refers to the correlation between the plotted variables.

Table III: Physical Depreciation

| | Hourly dep. (%) | Mean hrs. in a year | Annual dep. (%) |
|---|---|---|---|
| Australia | 0.0036 | 357 | 1.30 |
| Brazil | 0.0010 | 430 | 0.44 |
| Canada | 0.0030 | 293 | 0.88 |
| China | 0.0009 | 229 | 0.21 |
| Spain | 0.0013 | 464 | 0.59 |
| France | 0.0035 | 391 | 1.36 |
| Great Britain & Ireland | 0.0029 | 500 | 1.43 |
| Germany | 0.0043 | 543 | 2.36 |
| India | 0.0026 | 344 | 0.91 |
| Italy | 0.0017 | 265 | 0.45 |
| Mexico | 0.0010 | 340 | 0.34 |
| Netherlands | 0.0019 | 392 | 0.75 |
| New Zealand | 0.0040 | 503 | 2.03 |
| United States | 0.0034 | 223 | 0.75 |
| South Africa | 0.0013 | 690 | 0.90 |
| Average | 0.0024 | 397 | 0.98 |

The table shows hourly depreciation rates $e^{-\zeta_i}$, average hours of usage in a year $u_i$, and annual depreciation rates $e^{-\zeta_i}u_i$, for the countries in our sample.




(a) (b)

Figure VIII: Quality Adjustment of Agricultural Equipment. The figure compares our measures of quality-adjusted equipment stock to the HP-equivalent number of operated tractors provided by the USDA-ERS (panel a) and Larson et al. (2000)'s measures of agricultural fixed capital (panel b). The Larson et al. (2000) measures are averages for the 1985-1991 period. All measures are reported in per worker terms. *Corr* refers to the correlation between the plotted variables.

Table IV: Summary Statistics

| **Country** | **Observations** | **Cross Sections** | **Price** | **Age** | **Hours/year** | **Horsepower** |
|---|---|---|---|---|---|---|
| Australia | 2,108 | 2013-2017 | 41,138 | 10 | 357 | 135 |
| Brazil | 1,710 | 2013-2017 | 21,549 | 12 | 430 | 110 |
| Canada | 40,950 | 2008-2017 | 52,516 | 8 | 293 | 128 |
| China | 3,983 | 2017 | 7,520 | 3 | 229 | 90 |
| Spain | 817 | 2012-2017 | 24,312 | 15 | 464 | 110 |
| France | 2,604 | 2012-2017 | 34,851 | 11 | 391 | 120 |
| Great Britain & Ireland | 5,641 | 2011-2017 | 38,534 | 8 | 500 | 135 |
| Germany | 3,880 | 2013-2017 | 42,415 | 10 | 543 | 155 |
| India | 203 | 2016 | 3,890 | 10 | 344 | 45 |
| Italy | 337 | 2014-2017 | 21,524 | 14 | 265 | 95 |
| Mexico | 899 | 2013-2017 | 21,500 | 9 | 340 | 108 |
| Netherlands | 896 | 2012-2017 | 27,077 | 12 | 392 | 115 |
| New Zealand | 1,208 | 2015-2017 | 38,042 | 8 | 503 | 115 |
| United States | 549,314 | 2007-2017 | 44,500 | 10 | 223 | 140 |
| South Africa | 479 | 2016-2017 | 28,753 | 5 | 690 | 124 |
| **Overall** | **615,029** | | **43,962** | **9** | **233** | **137** |

The table shows country coverage and summary statistics for our dataset. We report median values for price, age, hours per year, and horsepower. Prices are expressed in USD. We merge the observations for Great Britain and Ireland due to sample size. We refer to these observations as Great Britain & Ireland. Line "Overall" presents the total number of observations, the median price, age, hours of usage per year and horsepower in the sample.

Table V: Empirical Age-Price Profile

| | Raw data (1) | Imputed data (2) |
|---|---|---|
| Country dummy * age: | | |
| ***Australia*** | -0.030 | -0.039 |
| | (0.0017) | (0.0014) |
| ***Brazil*** | -0.027 | -0.024 |
| | (0.0028) | (0.0012) |
| ***Canada*** | -0.042 | -0.045 |
| | (0.0003) | (0.0003) |
| ***China*** | -0.068 | -0.072 |
| | (0.0048) | (0.0033) |
| ***Spain*** | -0.037 | -0.036 |
| | (0.0025) | (0.0019) |
| ***France*** | -0.040 | -0.045 |
| | (0.0015) | (0.0011) |
| ***Great Britain & Ireland*** | -0.036 | -0.042 |
| | (0.001) | (0.0009) |
| ***Germany*** | -0.029 | -0.034 |
| | (0.0009) | (0.0012) |
| ***India*** | -0.037 | -0.037 |
| | (0.0033) | (0.0033) |
| ***Italy*** | -0.029 | -0.025 |
| | (0.0026) | (0.0034) |
| ***Mexico*** | -0.030 | -0.030 |
| | (0.003) | (0.0013) |
| ***Netherlands*** | -0.031 | -0.039 |
| | (0.0016) | (0.0013) |
| ***New Zealand*** | -0.034 | -0.040 |
| | (0.0014) | (0.0015) |
| ***United States*** | -0.038 | -0.041 |
| | (0.0001) | (0.0001) |
| ***South Africa*** | -0.056 | -0.071 |
| | (0.0066) | (0.0069) |
| Observations | 534,928 | 614,954 |
| $R^2$ | 0.901 | 0.895 |
| log-likelihood | -178,563 | -239,621 |

All regressions include country-year and manufacturer dummies. Horsepower is measured in hundreds, and hours per year are measured in tens of thousands. All regressions allow for a Box-Cox transformation on horsepower with coefficient $\xi$ in regression equation 1. Columns (1) and (2) use raw and imputed data. Robust standard errors are in parentheses.

## Table VI: Empirical Age-Price Profile, ctn'd.

| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country-year dummy** | | | | | | | | | | | |
| ***Australia*** | | | | | | | -0.150 | -0.219 | -0.291 | -0.249 | -0.208 |
| | | | | | | | (0.098) | (0.068) | (0.064) | (0.066) | (0.064) |
| ***Brazil*** | | | | | | | -0.680 | -0.697 | -0.871 | | -0.742 |
| | | | | | | | (0.052) | (0.065) | (0.072) | | (0.066) |
| ***Canada*** | | -0.167 | -0.262 | -0.080 | -0.039 | -0.028 | -0.043 | -0.016 | -0.074 | -0.023 | 0.080 |
| | | (0.055) | (0.065) | (0.063) | (0.062) | (0.062) | (0.062) | (0.061) | (0.061) | (0.061) | (0.061) |
| ***China*** | | | | | | | | | | | -1.734 |
| | | | | | | | | | | | (0.065) |
| ***Spain*** | | | | | | -0.568 | -0.343 | -0.329 | -0.607 | -0.512 | -0.435 |
| | | | | | | (0.081) | (0.068) | (0.065) | (0.051) | (0.068) | (0.061) |
| ***France*** | | | | | | -0.286 | -0.113 | -0.084 | -0.176 | -0.189 | -0.038 |
| | | | | | | (0.073) | (0.066) | (0.065) | (0.063) | (0.064) | (0.063) |
| ***Great Britain & Ireland*** | | | | | -0.317 | -0.291 | -0.284 | -0.233 | -0.343 | -0.331 | -0.258 |
| | | | | | (0.069) | (0.065) | (0.065) | (0.063) | (0.062) | (0.063) | (0.062) |
| ***Germany*** | | | | | | | -0.329 | -0.141 | -0.261 | -0.273 | -0.207 |
| | | | | | | | (0.085) | (0.064) | (0.064) | (0.064) | (0.065) |
| ***India*** | | | | | | | | | | -1.581 | |
| | | | | | | | | | | (0.107) | |
| ***Italy*** | | | | | | | | -0.447 | -0.607 | -0.402 | -0.394 |
| | | | | | | | | (0.069) | (0.051) | (0.055) | (0.067) |
| ***Mexico*** | | | | | | | -0.715 | -0.706 | -0.735 | -0.742 | -0.701 |
| | | | | | | | (0.076) | (0.067) | (0.069) | (0.071) | (0.068) |
| ***Neatherlands*** | | | | | | -0.236 | -0.293 | -0.339 | -0.407 | -0.365 | -0.229 |
| | | | | | | (0.070) | (0.079) | (0.072) | (0.067) | (0.070) | (0.067) |
| ***New Zealand*** | | | | | | | | | -0.235 | -0.178 | -0.217 |
| | | | | | | | | | (0.064) | (0.065) | (0.065) |
| ***United States*** | -0.313 | -0.266 | -0.260 | -0.231 | -0.194 | -0.159 | -0.129 | -0.058 | -0.083 | -0.081 | 0.000 |
| | (0.061) | (0.062) | (0.061) | (0.061) | (0.061) | (0.061) | (0.061) | (0.061) | (0.061) | (0.061) | (0.061) |
| ***South Africa*** | | | | | | | | | | -0.518 | -0.445 |
| | | | | | | | | | | (0.076) | (0.069) |

The table reports the estimates of the country-year dummies for the regression in column (2) of table V as differences from the estimate for the United States in 2017. Robust standard errors are in parentheses.

Table VII: Empirical age-price profile: Robustness.

| | **Benchmark** | | **Matched Sample** | | | **Box-Cox** |
|---|---|---|---|---|---|---|
| | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** |
| **Country Dummy * age** | | | | | | |
| ***Australia*** | -0.039 | -0.037 | -0.037 | -0.037 | -0.037 | -0.035 |
| | (0.0014) | (0.0041) | (0.0041) | (0.0041) | (0.0041) | |
| ***Brazil*** | -0.024 | -0.028 | -0.029 | -0.029 | -0.029 | -0.020 |
| | (0.0012) | (0.0046) | (0.0046) | (0.0042) | (0.0042) | |
| ***Canada*** | -0.045 | -0.048 | -0.048 | -0.048 | -0.048 | -0.040 |
| | (0.0003) | (0.0008) | (0.0008) | (0.0008) | (0.0008) | |
| ***China*** | -0.072 | | | | | -0.058 |
| | (0.0033) | | | | | |
| ***Spain*** | -0.036 | | | | | -0.031 |
| | (0.0019) | | | | | |
| ***France*** | -0.045 | | | | | -0.038 |
| | (0.0011) | | | | | |
| ***Great Britain & Ireland*** | -0.042 | -0.051 | -0.053 | -0.053 | -0.053 | -0.037 |
| | (0.0009) | (0.003) | (0.0032) | (0.0033) | (0.0033) | |
| ***Germany*** | -0.034 | -0.033 | -0.033 | -0.033 | -0.033 | -0.029 |
| | (0.0012) | (0.0014) | (0.0015) | (0.0014) | (0.0014) | |
| ***India*** | -0.037 | | | | | -0.030 |
| | (0.0033) | | | | | |
| ***Italy*** | -0.025 | -0.037 | -0.037 | -0.037 | -0.037 | -0.020 |
| | (0.0034) | (0.0034) | (0.0034) | (0.0034) | (0.0034) | |
| ***Mexico*** | -0.030 | -0.037 | -0.038 | -0.038 | -0.038 | -0.028 |
| | (0.0013) | (0.0061) | (0.0062) | (0.0062) | (0.0062) | |
| ***Netherlands*** | -0.039 | -0.033 | -0.033 | -0.033 | -0.033 | -0.034 |
| | (0.0013) | (0.0026) | (0.0026) | (0.0028) | (0.0028) | |
| ***New Zealand*** | -0.040 | | | | | -0.035 |
| | (0.0015) | | | | | |
| ***United States*** | -0.041 | -0.039 | -0.040 | -0.040 | -0.040 | -0.036 |
| | (0.0001) | (0.0002) | (0.0002) | (0.0002) | (0.0002) | |
| ***South Africa*** | -0.071 | | | | | -0.070 |
| | (0.0069) | | | | | |
| Controls | | | | | | |
| Wage | N | N | Y | N | Y | N |
| Crops | N | N | N | Y | Y | N |
| $\lambda$ | | | | | | 0.134 |
| | | | | | | (0.001) |
| Observations | 614,954 | 122,270 | 122,270 | 122,270 | 122,270 | 614,954 |
| $R^2$ | 0.895 | 0.871 | 0.871 | 0.872 | 0.872 | 0.903 |
| Log-likelyhood | -23,9621 | -28,339 | -28,339 | -27,983 | -27,983 | -6,779,000 |

Column (1) reports the benchmark estimates, as in column (2) of Table V. Columns (2) through (5) use our dataset matched with information on crop production and wages of repair workers. Column (6) reports estimates for a Box-Cox transform in prices; the entries for *Country dummy * age* are the price semi-elasticity to age computed for a synthetic tractor manufactured by John Deere and hours, horsepower, and age equal to the median in the sample. Column (7) reports estimates for country-specific regressions. $\lambda$ is the Box-Cox transform on tractor prices. Robust standard errors are in parentheses.

Table VIII: Empirical Age-Price Profile: Robustness, ctn'd.

| | **Benchmark** | | **Matched Sample** | | | **Box-Cox** |
|---|---|---|---|---|---|---|
| | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** |
| **Country Dummy * age** | | | | | | |
| ***Australia*** | -0.208 | 0.122 | 0.124 | 0.110 | 0.110 | -0.226 |
| | (0.0642) | (0.113) | (0.1129) | (0.1128) | (0.1128) | |
| ***Brazil*** | -0.742 | -0.084 | -0.090 | -0.120 | -0.120 | -0.689 |
| | (0.0656) | (0.0513) | (0.0511) | (0.0537) | (0.0537) | |
| ***Canada*** | 0.080 | 0.135 | 0.134 | 0.125 | 0.125 | 0.078 |
| | (0.0612) | (0.1106) | (0.1105) | (0.1103) | (0.1103) | |
| ***China*** | -1.734 | | | | | -1.559 |
| | (0.0652) | | | | | |
| ***Spain*** | -0.435 | | | | | -0.409 |
| | (0.0611) | | | | | |
| ***France*** | -0.038 | | | | | -0.094 |
| | (0.0632) | | | | | |
| ***Great Britain & Ireland*** | -0.258 | -0.150 | -0.180 | -0.197 | -0.197 | -0.262 |
| | (0.0624) | (0.1156) | (0.1167) | (0.1166) | (0.1166) | |
| ***Germany*** | -0.361 | -0.084 | -0.090 | -0.120 | -0.120 | -0.258 |
| | (0.0683) | (0.0513) | (0.0511) | (0.0537) | (0.0537) | |
| ***India*** | -1.540 | | | | | -1.369 |
| | (0.1143) | | | | | |
| ***Italy*** | -0.394 | -0.199 | -0.192 | -0.209 | -0.209 | -0.378 |
| | (0.0671) | (0.1288) | (0.1289) | (0.1288) | (0.1288) | |
| ***Mexico*** | -0.701 | -0.412 | -0.389 | -0.401 | -0.400 | -0.623 |
| | (0.068) | (0.1789) | (0.1794) | (0.1807) | (0.1807) | |
| ***Netherlands*** | -0.229 | 0.030 | 0.038 | 0.017 | 0.017 | -0.222 |
| | (0.0674) | (0.1183) | (0.1183) | (0.1183) | (0.1183) | |
| ***New Zealand*** | -0.217 | | | | | -0.242 |
| | (0.0648) | | | | | |
| ***United States*** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | (0.0612) | (0.1104) | (0.1103) | (0.1102) | (0.1102) | |
| ***South Africa*** | -0.445 | | | | | -0.380 |
| | (0.0695) | | | | | |

The table reports estimates of the intercept of the age-price profile net of that of the US for the regressions in Table VII. For India, the intercept is reported in 2016 and for all other countries it is reported in 2017. Robust standard errors are in parentheses.

Table IX: Home Trade Shares

| | Machinery | Equipment |
|---|---|---|
| Australia | 0.53 | 0.48 |
| Brazil | 0.82 | 0.85 |
| Canada | 0.62 | 0.61 |
| China | 0.94 | 0.95 |
| Spain | 0.77 | 0.76 |
| France | 0.78 | 0.74 |
| Great Britain & Ireland | 0.76 | 0.68 |
| Germany | 0.89 | 0.86 |
| India | 0.86 | 0.87 |
| Itali | 0.92 | 0.86 |
| Mexico | 0.56 | 0.84 |
| Netherlands | 0.73 | 0.65 |
| New Zealand* | 0.18 | . |
| United States | 0.85 | 0.80 |

The table reports 1 minus the ratio of imports to absorption, where absorption is gross output minus exports. The *Machinery* column reports this statistics for machinery equipment only, whereas column *Equipment* reports it for all equipment. Source: Our own computations based on national tables from the World Input Output Database, 2016. No available data for South Africa. *Own computations from Trade Policy Information System.

Table X: International Price Elasticity to Agricultural Labor Productivity

| logs | **(1)** | **(2)** | **(3)** | **(4)** |
|---|---|---|---|---|
| Agricultural labor productivity | 0.0743 | 0.0665 | 0.0799 | 0.0808 |
| | (0.00407) | (0.00509) | (0.00503) | (0.00504) |
| Distance | | 0.00635 | 0.264 | 0.263 |
| | | (0.00137) | (0.0127) | (0.0127) |
| Distance squared | | | -0.0166 | -0.0165 |
| | | | (0.000817) | (0.000814) |
| Trade agreement | | | | 0.00209 |
| | | | | (0.000282) |
| Intercept | -0.0112 | -0.0611 | -1.045 | -1.043 |
| | (0.000945) | (0.0107) | (0.0497) | (0.0496) |
| Observations | 13,812 | 13,812 | 13,812 | 13,812 |

The table reports estimates of the coefficients in regression equation 18. Columns (2) to (4) include gravity variables to control for trade barriers, one at a time. Robust standard errors are in parentheses.