

1. Introduction

The agricultural sector holds immense significance within the economies of Latin America, contributing substantially to GDP and employing a considerable portion of the labor force (World Bank, 2022). Notably, agricultural growth has emerged as a potent tool for poverty reduction in Latin America, outstripping growth from other sectors by a factor of 2.7 (World Bank, 2007). However, despite its pivotal role, the agricultural sector faces numerous challenges, including low productivity and limited output per worker, influenced by factors such as inadequate access to credit, and underutilization of technology (FAO, 2019).

A crucial bottleneck impeding agricultural productivity is land tenure insecurity, which is particularly pervasive in rural areas (Gignoux et al., 2013; Lawry et al., 2017). Empirical studies underscore that land tenure insecurity obstructs agricultural investment and productivity, especially among economically vulnerable family farmers (Gignoux et al., 2013; Quisumbing & Kumar, 2014). The absence of secure land rights poses hurdles to long-term investments, technology adoption, and access to credit for agricultural ventures (Besley, 1995; Deininger & Jin, 2006). Despite ongoing efforts, the lack of formal tenure security remains a prevalent issue in Latin America, particularly in rural areas. In Peru, for instance, 45% of farmers lacked land titles in 2012, while in Bolivia, 48% of titling remained incomplete among farmers in 2014. Similarly, 60% of Ecuadorian farmers did not possess property titles by 2008 (Corral & Montiel, 2022; IDB, 2019).

Despite the expanding literature on the subject, a clear empirical understanding of the causal impacts of tenure security on smallholder farm technical efficiency and productivity remains limited (Lawry et al., 2017). While some studies suggest positive outcomes, such as enhanced farm technical efficiency (Deininger & Chamorro, 2004; Goldstein & Udry, 2008; Higgins et al., 2018), others find no conclusive evidence of efficiency differences across varying land rights bundles (Gavian & Ehui, 1999; Place & Hazell, 1993). In part, these mixed results may be due to the underlying endogeneity that exists between tenure security and productive decisions (Coulibaly, 2021; Higgins et al., 2018; Lawin & Tamini, 2019; Leonhardt et al., 2019; Navarro-Castañeda et al., 2021). Particularly when it comes to the estimation of tenure security impacts on technical efficiency as a measure of total factor productivity of the farm, most empirical evidence has only been able to establish correlation, and not causation (Michler & Shively, 2014; Ghebru & Holden, 2015; Koirala et al., 2016). To our knowledge, no studies applying the appropriate methodologies to control for sources of endogeneity have been conducted to date for Latin America, a region with some of the highest land tenure insecurity in the world.

This study embarks on a nuanced exploration of the impact of formal land ownership on the technical efficiency and productivity of farmers in Latin America, focusing on three Andean countries, Bolivia, Ecuador, and Peru. Specifically, the research utilizes cross-sectional agricultural household data collected as part of monitoring and evaluation plans of national programs aimed at enhancing land administration systems. Surveys were conducted in 2014 and 2018, 2019, and 2023 for Ecuador, Peru and Bolivia, respectively, encompassing a sample of 5,288 farmer households, and detailed information on sociodemographic, land and production characteristics that allow us to estimate the farm's technical efficiency relative to the highest feasible output given a set of inputs and technology. In order to control for biases arising from observed and unobserved confounder, we employ a multi-stage empirical strategy that combines propensity score matching (PSM) with a sample selection bias corrected stochastic production frontier model (Greene, 2010) in the vein of Bravo-Ureta et al. (2006), Bravo-Ureta et al. (2021), and González-Flores et al. (2014). We then estimate meta frontiers to account for potential differences in technical efficiency between titled and untitled farmers as first proposed by Battese et al. (2004). Finally, we estimate the impact of holding legal land title on technical efficiency using Tobit regression models, which are complemented by a difference-in-difference approach in the

case of Ecuador, where two survey rounds are available. Additionally, mechanisms through which land tenure security may influence productivity, such as access to credit, investment in land, and incidence of land conflicts, are explored using probit models.

Positioned at the intersection of academia and policy, this research contributes valuable insights into the complex relationship between land tenure security and agricultural outcomes. By addressing critical gaps in the existing literature and employing a robust methodology, our findings aim to inform evidence-based policies that enhance both the efficiency and productivity of smallholder farmers, crucial for fostering sustainable rural development in the Andean region.

The remainder of the paper is organized as follows. In the next section, we outline the conceptual framework of our study. Section 3 provides a context of the history and current situation of land tenure security in Latin America. In section 4, we describe our data sources and summary statistics. In section 5, we detail the methodology and empirical approach. Results are presented in section 6, and conclusions are discussed in section 7.

2. Conceptual framework

Smallholder and family farms play a crucial role in safeguarding global food resources, especially in the face of the challenges posed by a growing world population and the adverse impacts of climate change. A widely accepted perspective asserts that effective strategies to combat poverty, ensure food security, and preserve natural resources rely on the active involvement of smallholder farmers (Birner & Resnick, 2010; FAO, 2014). This consensus is supported by several key factors. Firstly, smallholder farming, typically characterized by holdings smaller than 2 hectares, represents the predominant form of agriculture, constituting 84% of farms worldwide (Lowder et al., 2016). Covering 24% of total agricultural land, these farms make substantial contributions to global food production, accounting for 29% of crop production and 32% of the global food supply (Ricciardi et al., 2018). Secondly, smallholder farming often serves as the primary source of income for a significant portion of the world's most vulnerable populations (Hazell et al., 2010). Thirdly, empirical evidence supports the role of smallholder farming in ecosystem regulation and enhancing ecosystem resilience through crop and landscape diversity (Kapari et al., 2023; IFAD, 2013; Van Vliet et al., 2015).

Despite the critical role played by smallholder farming, these farms often face various constraints that impede crop productivity and efficient use of production inputs. Primary challenges include insufficient access to inputs and technologies, limited access to credit, and inadequate farm practices to mitigate the negative effects of pests, diseases, and climate shocks (FAO, 2019). One obstacle that has consistently been identified as one of the most crucial is land tenure insecurity (Gignoux et al., 2013; Lawry et al., 2017), since it hinders agricultural investment and productivity, particularly among impoverished family farmers who lack the certainty that they will be able to garner the benefit streams that emerge from the use of their land in the medium- to long term (Ghebru & Holden, 2015; Quisumbing & Kumar, 2014).

Economic theory identifies four routes through which securing property rights may influence agricultural productivity and efficiency. First, property rights provide an incentive to make long-term land investments and to adopt new production technologies that increase productivity in the long run (Besley, 1995; Deininger & Jin, 2006; Goldstein & Udry, 2008). Secondly, secure ownership may facilitate land use as collateral, thereby streamlining access to financial resources for farming activities (Feder & Feeny, 1991)¹. Third, clear ownership reduces the cost and risk of

¹ Notwithstanding the theoretical impact, empirically the evidence remains mixed. While some studies find land tenure security increases access to financial markets (Feder & Feeny, 1991; Schling & Pazos, 2021), others find the opposite relationship (Lawry et al., 2014; Trivelli et al., 2004; Sanjak, 2012).

land transfers, improving factor intensity and potentially enhancing efficiency through the reallocation of land to more capable farmers through rental markets (Abdulai et al., 2011; Deininger, 2003). Furthermore, secure land ownership reduces the risk of legal land conflicts, freeing up farmers to allocate their resources more efficiently toward productive activities (Besley & Ghatak, 2010) and preventing overinvestment in protective measures (Malik & Schwab, 1991). Consequently, promoting productive and efficient farmland use becomes a paramount policy consideration for addressing food security and poverty alleviation.

Increases in agricultural productivity can be brought about in two ways. On the one hand, a farmer may increase the efficiency with which he or she uses existing inputs to production, such as seeds, fertilizers, machinery, or labor. The other source of productivity improvements stems from technological change, wherein the same inputs are able to generate higher levels of production thanks to the adoption of more efficient agricultural technologies or practices. With regards to tenure security enabling higher technical efficiency as a source of higher levels of productivity, one may then expect that access to credit markets, as well as the reduction of land conflicts, would enable farmers to use their existing inputs in a more efficient manner (Bravo-Ureta et al., 2021; Feder & Feeny, 1991). Similarly, establishing a functioning land market may increase productivity by allocating land rights to a farmer that can use it more efficiently (Abdulai et al., 2011; Ali et al., 2011). In contrast, the adoption of new production technologies and land investments are more likely to lead to technological change that would expand the possible production frontier of a farmer's production system (Ghebru & Holden, 2015).

Despite the supposed benefits of tenure security to increasing agricultural productivity, Latin America and the Caribbean continues to grapple with high levels of land tenure informality and insecurity to this day, particularly in rural areas (Corral & Montiel, 2022). Although comprehensive data do not exist on this matter, some examples illustrate the situation. In 2022, in Peru, 65% of agricultural producers did not have a property title, and only 20% of producers had a property title registered in Public Registries (INEI, 2023). Similarly, in Guatemala, it is estimated that, by 2015, 40% of rural plots were not yet titled (World Bank, 2015). Furthermore, by 2016, 30% of the agricultural land of Bolivia still awaited to be regularized, titled, and registered (IDB, 2016). Lastly, by 2008, less than 40% of agricultural plots in Ecuador had a formal title (Corral & Montiel, 2022). Despite widespread land reforms during the 1960s and 1970s in the region, smallholder farmers were largely absent from the new agrarian structures (De Janvry & Sadoulet, 1998). Additionally, many land administration systems in the region still face significant challenges, such as incomplete or inaccurate information on land and limited sharing of this information between cadastral and property registration institutions, as well as limited institutional capacity to perform the basic functions of a modern land administration system.

Motivated by the recognition that insufficient land rights hinder agricultural development, numerous developing countries and international development agencies have given precedence to the formalization of land rights through the registration and certification of agricultural land as top priorities in their development agendas. The World Bank's commitment to land tenure projects amounted to 1.8 billion dollars between 1995 and 2006 (Bell, 2006). In Latin America, the Inter-American Development Bank has endorsed various projects, allocating a total of 500 million dollars for this purpose. The majority of these programs were designed to enhance land administration systems and confer titles to the land as a means to bolster tenure security of smallholder farmers.

Despite the expanding literature, a clear empirical understanding of the causal impacts of increased tenure security through such programs on smallholder farm technical efficiency and productivity remains limited (Lawry et al., 2017). While some studies affirm positive outcomes, such as improved farm technical efficiency (Deininger & Chamorro, 2004; Goldstein & Udry, 2008; Higgins et al., 2018), others find no conclusive evidence of efficiency differences across varying

land rights bundles (Place & Hazell, 1993; Gavian & Ehui, 1999), or emphasize the importance of considering contextual factors in land regularization effectiveness (Fort, 2007; Hong et al., 2020; Suchá et al., 2020; Zegarra et al., 2008). Challenges arise in estimating causal effects due to endogeneity between tenure security and productive decisions, particularly in cross-sectional studies which often establish correlation rather than causation (Higgins et al., 2018; Leonhardt et al., 2019; Navarro-Castañeda et al., 2021).

Only a select number of studies have applied experimental and quasi-experimental methods to isolate the causal impacts of land regularization interventions (see, for instance: Goldstein et al., 2015; Holland et al., 2017). Particularly when it comes to the estimation of tenure security impacts on technical efficiency as a measure of total factor productivity of the farm, most empirical evidence has only been able to establish correlation, and not causation. For instance, recent studies in Ethiopia and the Philippines find a positive impact of tenure security on farm efficiency, but these works fail to account for underlying biases (Michler & Shively, 2014; Ghebru & Holden, 2015; Koirala et al., 2016). Notable exceptions are studies conducted by Coulibaly (2022) and Lawin and Tamin (2019), which relied on econometric methods including Greene's (2010) bias-correcting SPF model as well as PSM techniques to successfully address endogeneity. The two studies find inconsistent effects of land tenure security on farm efficiency for the cases of Benin and Burkina Faso. To our knowledge, no such rigorous studies have been conducted for Latin America to date.

In summary, more research is needed on the impacts of tenure security on technical efficiency of the agricultural production systems of smallholder farmers, particularly in the Latin American region. In order to appropriately estimate this causal relationship, one should carefully consider the context of the established land tenure system and existing efforts to promote land regularization in the studied country. Additionally, care must be taken to select an empirical framework that makes it possible to control for various sources of endogeneity that may bias impact estimates. The following two sections therefore describe the regional context in Latin America and the Andean region in particular with regards to their history of land rights, and how past and current efforts for land regularization have affected tenure security among smallholder farmers. We then describe in detail how our empirical model addresses potential sources of selectivity bias in order to estimate a causal relationship between tenure security and technical efficiency for the case of Bolivia, Ecuador and Peru.

3. Land tenure systems in Latin America

Latin America has a deeply rooted history of colonialism and elimination of its original indigenous land systems, which has contributed to pervasive land inequality across the region. Presently, Latin America stands out as the most unequal region worldwide in terms of land distribution. The Gini coefficient for land ownership in the region is alarmingly high, reaching 0.79 on average, with Central America averaging at 0.75 and South America at 0.85 (Guereña, 2016). By the beginning of the twentieth century, the predominant land regime in the region was a latifundia system wherein the few rural elites dominated land ownership by means of large estates whose agricultural production was facilitated by the labor of the large majority of small peasant farmers and landless rural workers (Botella-Rodríguez & González-Esteban, 2021). Against the backdrop of political upheaval across the region caused by the general discontent and severe poverty of peasant farmers, which in some countries resulted in government overthrow or civil war, the period of 1930 to 1970 was characterized by the implementation of wide-reaching land reforms. Particularly in the early 1960s, land reform was considered an effective instrument to foster economic growth in an attempt to counteract the popular discontent with economic and social inequality (De Janvry, 1981; Díaz, 2000). In general, these land reforms aimed to redistribute land

from large landholders, often by forced expropriation, to smallholder farmers with the objective of redistributing wealth, raising living standards, and stimulating economic growth (Sieg, 2009).

Despite these efforts, success stories² are scarce, with the overarching result being a failure to improve access to land and regularize land tenure among smallholder farmers (De Janvry & Sadoulet, 1998). More successful and sustainable land reforms, for instance in East Asia, highlight that land reforms in Latin America at the time failed to actively include all stakeholders in the redistribution process, often relying on large-scale expropriation without compensation, which increased opposition from the landed elite and undermined the reform process (Sieg, 2009). Additionally, these policies often failed to secure legal recognition of property rights, thereby hindering access to the various benefits of tenure security, including the establishment of efficient land markets and access to credit with land as collateral.

Since then, policymakers have grappled with how to ensure that land regularization efforts can be effective tools to stimulate economic growth in general and agricultural productivity in particular. Establishing legal tenure security and functional land markets has become a central tenet of effective land administration policies, and efforts have increasingly turned towards ensuring that land regularization be inclusive to vulnerable groups, including women and indigenous communities. Worldwide, efforts to promote comprehensive government-led land regularization and administration programs to enhance tenure security and improve agricultural productivity have been supported by multilateral development organizations including the World Bank and the Inter-American Development Bank with the aim of contributing to sustainable agricultural development and poverty alleviation in Latin American countries. In recent years, the Inter-American Development Bank (IDB) has played a pivotal role in advancing land administration programs across the Andean region, notably in Bolivia, Ecuador and Peru.

In Bolivia, the more recent history of rural land regularization and titling began in 1996 with the enactment of a National Agrarian Reform Service Law, which formally reconciled the demands of the rural majority and created the National Agrarian Reform Institute (INRA) as the entity in charge of implementing the Law. Though efforts for a more equitable land distribution go as far as back as the agrarian reform of 1952, progress was slow and did not include provisions for indigenous farmers. By the 1970s, only 45% of campesino farmers had received title. With the redesign of the institutional framework for land administration in 1996, and the third agrarian reform implemented ten years later in 2006, the Government of Bolivia was able to make significant strides in the regularization, cadaster, titling, and registration of rural lands. The changes made to the land tenure structure between 1992 and 2023 have helped narrow the gaps in land access for smallholders and Indigenous communities. In that period, the percentage of agrarian properties that were small properties or community properties rose from 10% (17 million hectares) to 26% (26.6 million), while the share of enterprises and medium-sized properties fell from 68% to 15%. Indigenous peoples, who were among the stakeholders left out of the 1952 agrarian reform, today own 25% of the regularized areas (25.6 million hectares), and the percentage of agrarian properties owned by women rose from 10% to 45%. The remaining 26% are public lands, which include the country's protected areas. Fully 92% of the 103,357,554 hectares that were to be regularized in the country already have been regularized.

IDB began supporting the Bolivian government with financial and technical support in their land regularization efforts in 2002, and in total approved and implemented three sovereign loans to advance rural land regularization and titling in the country, for a total loan amount of US\$109

² Mexico's land reform was the first in Latin America to address significant land inequality (Botella-Rodríguez & González-Esteban, 2021).

million. The latest loan, entitled *Rural Land Regularization and Titling Program* and approved in 2016, aimed to title 121,000 rural properties. In 2023, 13% of the total area, or 13.3 million hectares, remained to be regularized, titled and registered, for which purpose a new IDB loan of a value of US\$40 million is to be approved in early 2024. This loan, entitled the *Land Management Program for Sustainable Rural Development*, aims to increase income and food security of family farmers by regularizing and titling the remaining rural land area in Bolivia, primarily in the department of La Paz.

Land reform in Ecuador stretches back to the 1960s and 1970s, when the country first implemented comprehensive agrarian reforms to redistribute arable land to smallholder and indigenous farmers and transition towards a market-based land regime. Nevertheless, tenure irregularity remained high into the twenty-first century, as 58% of rural plots were not properly registered and titled in 2010, a situation that primarily affected smallholder farmers (IDB, 2010). To address this issue, the Government of Ecuador began implementing a pilot land administration program, the *Rural Land Regularization and Administration Program* (PRAT), in 2002 with financial and technical assistance from the IDB. This program tested and effectively implemented a so-called “sweep” methodology, which used comprehensive canton-level cadaster sweeps to regularize land tenure and register properties (Corral & Montiel, 2022). After PRAT’s successful regularization of properties in eight cantons, the Government of Ecuador in 2012 launched a nationwide land legalization program employing the methodologies honed during the implementation of PRAT. This Program, entitled the *National System for Rural Land Information and Management and Technology Infrastructure (Sistema Nacional de Información y Gestión de Tierras Rurales)*, also known as the SigTierras Program, represented the first phase of this effort and received financial support from the Inter-American Development Bank in the order of US\$90 million. With the objective of increasing productive efficiency and income of rural households as well as improving the overall performance of the rural economy, Sigtierras aimed to apply the sweep methodology to 50 cantons and consisted of three primary components: (i) cadastral mapping, (ii) reorganization of and investment in cadasters and property registries, and (iii) regularization of land titles.

By the close of the program in 2016, 55 cantons had completed a cadaster according to the Ministry of Agriculture (MAG), and 59 cantons were integrated into the National Land Information System. The first stage of regularization efforts, meaning the cadaster sweep, required significant time, so that the time in which each canton began the cadaster sweep ranged from 2012 until 2016. Even though a total of 163,580 parcels had initiated the regularization process by the end of the project, which was close to its target of 170,000, only 39,267 parcels had regularized their legal ownership status, representing only 23% of the initial program goal (Corral & Montiel, 2022). Even though the Program fell short of its objective to formalize land tenure by a large margin, the successful initiation of the regularization process implied that more than 160,000 digital parcel maps were issued to parcel owners with community assent.

Peru similarly first implemented massive agrarian land reforms in the 1960s and 1970s to redistribute land from private haciendas to rural communities. Despite these reforms, inequality in land access remains prevalent decades later; in 2022, 65% of farmers did not have a property title, and only 20% of producers had a property title registered in Public Registries (INEI, 2023). Since the early 1990s, the Peruvian government has implemented a nationwide *Land Titling and Registration Program (Programa de Titulación y Registro de Tierras, PTRT)* with support from IDB, which in its first two phases titled approximately 1.9 million properties on the Pacific coast and in the Andean highlands (Sierra region) between 1993 and 2007. The Program’s third phase was launched in 2015 and aimed to provide registered property titles to 214,000 individual farmers, 331 native communities, and 168 campesino communities located in the Andean and Amazon regions of Peru but was eventually shelved in 2022 due to implementation issues.

While efforts to regularize land tenure in the Andean countries is still ongoing, significant advances have occurred in recent years. It is therefore particularly relevant to assess how these land administration efforts may have impacted technical efficiency of production systems of smallholder farmers in this region, to better understand how secure land tenure can contribute to higher productivity and food security in the region.

4. Data description

4.1. Data sources

Our study relies on rich agricultural household data collected from approximately 6,700 farmer households in Andean countries including Bolivia, Ecuador, and Peru. In particular, for each of these countries, data were obtained through agricultural household surveys collected as part of the impact evaluation strategy of land administration programs that were being implemented with support from IDB, i.e. the *Land Management Program for Sustainable Rural Development* in Bolivia, the Sigtierrez Program in Ecuador and Phase 3 of PTRT in Peru. The purpose of the surveys was to characterize production systems and land tenure situation of smallholder farmers in these regions, so the questionnaires collected detailed information on agricultural production and land characteristics as well as sociodemographic information of farmers and their households. The survey design was based on the World Bank's Living Standard Measurement Study – Integrated Survey on Agriculture (LSMS – ISA), and, broadly speaking, each survey was composed of the following 11 modules: Household roster and sociodemographic characteristics, household economic activities, information on plots (including ownership), agricultural production (temporary and permanent crops), livestock, forestry production, remittances, credits and savings, asset ownership and dwelling characteristics, organization and association memberships, as well as food security and women's empowerment. The survey samples were selected to be statistically representative of the area where the land administration programs were to be implemented; for Bolivia, this implied that the survey was representative at national level³, for Ecuador, largely the highlands (or Sierra) region⁴ of the country, and for Peru, the Andean and Amazonas regions⁵. For our purposes, the availability of various socioeconomic and productive variables allows us to control for potential differences in such characteristics across households to better identify the effect of landownership on technical efficiency.

In the case of Bolivia, an agricultural household survey was conducted between April and June of 2023 with the purpose of evaluating the impact of the two most recent land administration programs implemented between 2016 through 2025. The sampling design relied on information of close to 20,000 communities nationwide from the most recent 2013 agricultural census, as well as updated data on the remediation and titling status of land therein. Taking into account the considerable progress that had been made towards regularizing rural land in the last two decades, the survey sample was stratified into three clusters: Cluster 1 consisted of communities located in the department of La Paz, where a majority of remaining land yet to be titled through the *Land Management Program For Sustainable Rural Development* was located (982 communities); Cluster 2 included communities where a large share of land had been titled prior to the implementation of the *Rural Land Regularization and Titling Program* in 2016 (6,632 communities); lastly, Cluster 3 consisted of communities where a large share of land was titled by

³ The survey included three sampling clusters, one for the department of La Paz where a large share of land remains to be titled, and two clusters for households titled prior to 2016 and between 2016 and 2022 respectively, distributed across the remaining eight departments of Bolivia.

⁴ More precisely, 10 of 11 sampled provinces were located in the Highlands, including Carchi, Imbabura, Pichincha, Santo Domingo de los Tsáchilas, Cotopaxi, Tungurahua, Bolívar, Chimborazo, Cañar, Azuay, and Loja. Additionally, one province from the Amazonas region (Morona Santiago) was sampled as well.

⁵ The survey in Peru was conducted in six departments: Apurímac, Cajamarca, Cusco, Puno, and San Martín.

the *Rural Land Regularization and Titling Program*, between 2016 and 2022 (11,971 communities). The sample was further stratified by department⁶ and a high or low level of crop diversification⁷. Approximately 90 communities were selected for each of the three clusters (80 in cluster 1, 94 in cluster 2, and 90 in cluster 3), and 9 farmer households were then randomly selected from each of these communities to take part in the survey. Upon completion of the survey, a total sample size of 2,283 households was achieved, distributed to 686 households in Cluster 1, 812 households in Cluster 2, and 785 households in Cluster 3. In this sample, 34% of farmers reported having legal title to at least one plot.

For Ecuador, two rounds of household surveys were collected in the context of the SigTierras Program's impact evaluation. The evaluation design proposed an identification strategy that would select a treatment and comparable control group at the canton level, since randomization at canton or household level was not possible, given that participation in the program was based on the demand of municipality governments so that all households located within the borders of selected cantons would automatically participate in cadaster and title regularization activities. The selection of participant cantons included several stages. After 171 cantons interested in participating in the program had completed an application process, a total of 47 cantons were selected for participation in the SigTierras Program based on a number of factors, including the budgetary limitations of SigTierras, the timely completion of the canton's application and negotiation process, and the availability of high-resolution digital aerial photographs, which was mainly impeded by continuous cloud cover in certain cases. Of the 47 treated cantons, 9 cantons were selected for the impact evaluation's treatment group to be geographically representative. To identify a valid counterfactual, the control group was then selected from 121 cantons that remained in the list of cantons which had completed the application process but had not been chosen to participate due to the factors named above. Using information on socioeconomic variables from the 2001 and 2010 National Censuses, a Propensity Score was constructed, and four control cantons were matched to each of the nine treated cantons (so each treated canton had 4 possible control cantons assigned). From these four control cantons per treated canton, the SigTierras' implementation team selected the one they considered the most similar to each of the treatment cantons, resulting in a final selection of 9 control cantons.

A sample of households was selected from treated and control cantons, respectively. For the treatment group, this selection was conducted among such households that, based on the cadaster sweep conducted for the program, had reported having at least one parcel with land tenure issues. Cadastral information on location and number of eligible households was used to identify census tracts with 12 or more eligible households. In total, 110 census tracts were identified. In each tract 12 eligible households were randomly selected for the treatment group (and 12 eligible households as back-up), leading to a total of 1,356 selected treated households. In order to select households from the nine cantons of the control group, information from the national censuses was used to estimate propensity scores for all available 754 census tracts to select three comparable control units per each treated census tract, based on the nearest-neighbor matching technique. In this case, one of the three matched census tracts would serve as the primary control unit, and the remaining two would serve as backup in case less than 12 households could be interviewed within the census tract. Again, only households reporting similar tenure issues as the treated households were selected for the control group. As a result, the selected control group contained 1,356 households, so that the evaluation sample of treatment and control units consisted of a total of 2,712 households. For this sample, a baseline survey was

⁶ Bolivia is subdivided into 9 departments: Beni, Chuquisaca, Cochabamba, La Paz, Oruro, Pando, Potosí, Santa Cruz, and Tarija.

⁷ This was measured by the Simpson diversification index (SDI); the sample was divided between high and low SDI according to the sample median of SDI=0.69.

carried out in 2014, while the follow-up survey was administered in 2018, two years after the closure of the program. At baseline, 49.9% of sampled farmers were found to own land without formal title, while this share decreased to 40.7% at endline.

For Peru, agricultural household survey data was collected in October and November of 2019 as part of the evaluation baseline for PTRT’s third phase among 2,385 smallholder farmers.⁸ Since the survey represented the baseline for the impact evaluation of PTRT Phase 3, the sample was equally distributed between a treatment and control group (1,194 treated, 1,191 control). Treated farmers were randomly selected from 80 pre-established Territorial Units designed to group parcels to be titled in a given geographic area. Farmers in the control group were selected from nearby zones with similar productive, socio-economic, and climatic characteristics, ensuring that none of the selected parcels had been determined to receive titling during Program implementation. This process took into account the excess demand for titling that still existed in intervention areas, making it possible that comparable parcels could be identified that would not have been offered titling through the program due to budgetary restraints. Given that the survey was conducted as part of an effort to characterize farmers who still required assistance with formalizing their plots in the future, the sample selection focused on such households where at least one of their plots had yet to receive formal title. In total, less than 10% of the households in this sample had property titles for at least one plot at the time of the survey.

To summarize, Table 1 shows sample sizes for each of the countries and collection waves.

Table 1: Sample Sizes

Country	Year of survey	Number of households
Bolivia	2023	2,283
Ecuador (baseline)	2014	2,687
Ecuador (endline)	2018	2,470
Peru	2019	2,385

In line with the specific objectives of the study, the majority of the analysis relies on the baseline surveys conducted in the three countries⁹. Additionally, we limit the sample for the purpose of our analysis to those households who own at least one plot (excluding 924 farmers) and are actively engaged in agricultural and/or livestock activities (excluding 867 farmers).¹⁰ Furthermore, households with yields exceeding the 95th percentile of the distribution in each country are excluded from the analysis (excluding 276 farmers). Consequently, at baseline, the final sample comprises a total of 5,288 households, with 1,591 in Peru, 2,353 in Ecuador, and 1,344 in Bolivia.

4.2. Descriptive statistics

Table 2 presents descriptive statistics outlining the sociodemographic, land, and productive characteristics of households within our study sample. Predominantly, households are headed by males, constituting approximately 80% of all households across the three countries. The average age of household heads is 53 years, with an educational attainment ranging from 5 to 6 years on average. On average, households consist of 3 members in Peru and Bolivia, and 4 members in

⁸ The survey was also conducted among 33 campesino communities (for 431 households) and 172 native communities (1,699 households).

⁹ I.e., the endline survey in Ecuador will only be used to the complementary panel analysis as discussed in Section 5.3.1.

¹⁰ Farmers encompassing those who cultivated a minimum of 0.1 hectares of prevalent crops within each respective country, coupled with ownership of livestock quantified in tropical livestock units.

Ecuador. There exists notable disparity among countries in terms of income diversification, with 20% of households in Bolivia, 50% in Ecuador, and 81% in Peru deriving income from non-farm activities, respectively.

Table 2: Descriptive Statistics

Country	Bolivia	Ecuador	Peru
A. Socioeconomic Characteristics			
Household head is a woman	0.20 (0.40)	0.22 (0.41)	0.20 (0.40)
Age of household head	53.67 (15.31)	52.38 (16.42)	53.53 (15.30)
Household head is married	0.81 (0.39)	0.73 (0.45)	0.74 (0.44)
Education of household head (in years)	5.82 (4.49)	5.11 (3.35)	6.17 (3.89)
Number of household members	3.20 (2.01)	4.34 (2.31)	3.00 (1.63)
% of households with non-farm income	0.20 (0.40)	0.50 (0.50)	0.81 (0.39)
Total annual labor income (in US\$)	2,628.10 (2,618.67)	3,230.36 (8,016.75)	3,842.88 (2,612.92)
Notes: Standard deviation in parentheses. All monetary values expressed in 2022 PPP USD.			

In terms of land ownership, a significant majority of sampled households in Ecuador and Bolivia possesses formal land titles, comprising 52% and 58% respectively, while only 10% of households in Peru¹¹ hold such titles. On average, farmers in these countries hold between 2 and 3 plots, with an average size of 4.6 hectares in Ecuador, and slightly larger plot sizes of 5.2 and 6.7 hectares respectively in Bolivia and Peru. A majority of farmers in all three countries obtained their land either through purchase or inheritance: in Peru, 46% of farmers purchased and 48% inherited their land, while in Ecuador, 44% of land was purchased and 50% inherited, and 24% of land was purchased and 66% inherited in Bolivia. Only 14% and 19% of farmers irrigated their plots in Peru and Ecuador, while 26% used irrigation in Bolivia. Since all three Andean countries are characterized by their largely mountainous terrain, it is unsurprising that between 53 and 75% of plots are sloped. In terms of land investments that farmers undertook in the last year, only 5 and 7% of farmers reported doing so in Peru and Ecuador, respectively. By contrast, 54% of Bolivian farmers reported having undertaken investments in their land, likely due to a larger share of the sample recently having completed titling as described in the previous subsection.

In terms of agricultural production, sampled farmers dedicate 0.83, 1.44, and 3.25 hectares to agricultural production on average in Peru, Ecuador, and Bolivia, respectively. The average annual crop production ranges from 2,200-2,500 kg, with significant variability observed within and between countries. Peruvian households demonstrate the highest average agricultural production per household, followed by Bolivia and Ecuador. The value of annual production ranged from US\$1,170 in Ecuador to US\$1,793 in Bolivia. Agricultural yields appeared quite

¹¹ The relatively low share of title holders in Peru can be attributed to the identification strategy of the sample selection in this country (see Section 4.1) and therefore is not representative of legal landownership at the national level.

similar in Peru and Bolivia, with around US\$1,210-1,220 per hectare, while yields in Ecuador appeared significantly lower at an average of US\$891 per hectare.

Access to markets was fairly similar in all three countries, with Bolivia showing the highest share of products sold in markets with 42%, followed closely by Ecuador with 38%, and Peru with 29%. Additionally, Bolivian farmers exhibit a higher propensity for adopting modern agricultural practices, as evidenced by higher usage of both organic and chemical fertilizers, as well as tractor use. Access to credit plays a pivotal role in agricultural productivity, with a higher percentage of households in Ecuador and Bolivia (29%) having accessed credit compared to Peru (7%). These nuanced variations underscore the importance of contextual factors in shaping agricultural production and productivity dynamics within the Andean region.

Table 2: Descriptive Statistics – Cont.

<i>Country</i>	<i>Bolivia</i>	<i>Ecuador</i>	<i>Peru</i>
A. Land Characteristics			
Plot size (in hectares)	6.7 (16.33)	4.61 (9.22)	5.15 (10.65)
Number of plots owned by household	2.94 (2.07)	2.74 (1.84)	2.18 (1.43)
% households with any land tenure document	-	0.62 (0.48)	1.00 (0.00)
% households with legal land title	0.58 (0.49)	0.52 (0.50)	0.10 (0.30)
% of plots obtained through purchase	0.24 (0.41)	0.44 (0.42)	0.46 (0.47)
% of plots obtained through inheritance	0.66 (0.46)	0.50 (0.42)	0.48 (0.46)
% of plots obtained through squatting	0.00 (0.03)	0.01 (0.09)	0.00 (0.05)
% of plots obtained through other means	0.10 (0.30)	0.05 (0.19)	0.05 (0.20)
% of irrigated plots	0.26 (0.44)	0.19 (0.40)	0.14 (0.35)
% of plots with slope	0.53 (0.50)	0.75 (0.43)	0.69 (0.46)
% of plots that received investment in the last year	0.23 (0.42)	0.07 (0.26)	0.05 (0.22)
% of households who faced land conflicts	-	0.12 (0.33)	0.04 (0.18)
Notes: Standard deviation in parentheses. All monetary values expressed in 2022 PPP USD.			

Table 3 presents descriptive statistics by land tenure status, dividing households into those with and without formal land titles, and presenting simple t-tests for the difference between the two groups. As mentioned, Peruvian households with land titles represent a minority (10%) in the sample. Conversely, in the study samples for Ecuador and Bolivia, the distribution is more balanced, with roughly half of the households holding land titles.

Table 2: Descriptive Statistics – Cont.

Country	Bolivia	Ecuador	Peru
A. Productive Characteristics			
Surface area harvested in last year (in ha)	3.25 (23.80)	1.44 (5.98)	0.83 (1.31)
Volume of annual agricultural production (in kg)	2,428.11 (6,939.75)	2,259.37 (4,836.29)	2,512.40 (3,872.63)
Value of annual agricultural production (in US\$)	1,793.09 (4,214.76)	1,169.71 (1,946.83)	1,320.96 (1,714.43)
Annual agricultural productivity (in kg/Ha)	2,779.95 (7,276.60)	3,858.31 (12,197.73)	6,071.65 (5,586.08)
Annual agricultural productivity (in US\$/Ha)	1,212.75 (1,963.00)	891.91 (1,469.51)	1,219.47 (2,639.54)
% of production sold	0.42 (0.49)	0.38 (0.49)	0.29 (0.46)
% of organic fertilizer use	0.68 (0.47)	0.39 (0.49)	0.38 (0.49)
% of chemical fertilizer use	0.24 (0.43)	0.27 (0.44)	0.07 (0.26)
% of tractor use	0.52 (0.50)	0.24 (0.43)	0.22 (0.41)
% of paid labor use	0.37 (0.48)	0.35 (0.48)	0.70 (0.46)
% of access to credit	0.29 (0.45)	0.29 (0.45)	0.07 (0.26)
Number of observations	1,344	2,353	1,591
Notes: Standard deviation in parentheses. All monetary values expressed in 2022 PPP USD.			

Comparing socioeconomic characteristics, notable variations emerge among households with land titles across the different countries. In Peru, households possessing land titles exhibit a lower prevalence of female household heads compared to those without title, whereas in Ecuador, the trend reverses, with a higher proportion of female heads in titled households. Conversely, in Bolivia, no significant disparity is observed in this regard. Moreover, in both Ecuador and Bolivia, households holding land titles tend to display lower levels of educational attainment than those without titles, a pattern not observed in Peru. Additionally, when considering total labor income, no discernible discrepancy arises between households with and without land titles across the three countries.

Table 3: Descriptive Statistics by Land Tenure Status

Variables	I. Bolivia			II. Ecuador			III. Peru		
	No Land Title	Land Title	Diff.	No Land Title	Land Title	Diff.	No Land Title	Land Title	Diff.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Count of Households	569	775		1,123	1,230		1,437	154	
Share of Household	0.42	0.58		0.48	0.52		0.90	0.10	
A. Socioeconomic Characteristics									
Household head is female	0.20 (0.40)	0.19 (0.39)	-0.01	0.20 (0.40)	0.24 (0.43)	0.04**	0.21 (0.41)	0.13 (0.34)	-0.08**
Education of household head (in yrs.)	6.40 (4.54)	5.39 (4.40)	-1.00***	5.44 (3.40)	4.81 (3.28)	-0.63***	6.16 (3.92)	6.27 (3.60)	0.11
Total annual labor income (in US\$)	2,825.95 (2,461.62)	2,377.05 (2,795.74)	-448.9	3,166.25 (6,512.94)	3,292.55 (9,249.11)	126.3	3,843.50 (2,637.80)	3,836.54 (2,353.92)	-6.95
B. Land Characteristics									
Plot size (in ha)	3.27 (8.72)	9.21 (19.80)	5.94***	4.59 (9.96)	4.63 (8.49)	0.04	5.07 (10.60)	5.87 (11.12)	0.80
% of land irrigated	0.20 (0.40)	0.31 (0.46)	0.11***	0.12 (0.32)	0.26 (0.44)	0.15***	0.14 (0.34)	0.19 (0.39)	0.05*
% of plots that received investment	0.19 (0.39)	0.26 (0.44)	0.07***	0.06 (0.24)	0.08 (0.27)	0.02**	0.04 (0.21)	0.10 (0.31)	0.06***
% of HH who faced land conflicts	-	-	-	0.09 (0.29)	0.15 (0.35)	0.05***	0.03 (0.18)	0.06 (0.24)	0.03*
Notes: Standard Deviation in parentheses. All monetary values expressed in 2022 PPP USD. Columns 3, 6 and 9 display the difference in means between groups. Difference unequal to zero if p-value significant at the 99 (***), 95 (**), or 90 (*) confidence level.									

Table 3: Descriptive Statistics by Land Tenure Status – Cont.

Variables	I. Bolivia			II. Ecuador			III. Peru		
	No Land Title	Land Title	Diff.	No Land Title	Land Title	Diff.	No Land Title	Land Title	Diff.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
A. Productive Characteristics									
Surface area harvested (in ha)	1.92 (6.57)	4.18 (30.50)	2.26	1.25 (2.52)	1.61 (7.82)	0.37	0.82 (1.30)	0.90 (1.36)	0.08
Annual Production Volume (Kg)	1,066.61 (3,133.20)	3,378.96 (8,531.72)	2,312.35***	2,274.32 (4,842.24)	2,246.38 (4,833.59)	-27.94	2,382.82 (3,757.49)	3,536.62 (4,575.39)	1,153.80***
Annual Production Value (USD)	1,400.02 (3,448.15)	2,081.69 (4,679.86)	681.67***	975.93 (1,752.09)	1,346.63 (2,094.09)	370.70***	1,307.76 (1,706.05)	1,444.09 (1,791.82)	136.33
Agricultural Productivity (Kg/Ha)	2,422.36 (5,530.59)	3,029.69 (8,275.38)	607.32	3,572.19 (14,183.01)	4,113.30 (10,106.99)	541.11	6,117.15 (5,700.73)	5,757.14 (4,730.33)	-360.01
Agricultural Productivity (USD/Ha)	1,388.26 (2,213.22)	1,083.88 (1,747.07)	-304.38***	957.85 (1,566.31)	831.71 (1,373.08)	-126.14**	1,261.52 (2,703.45)	827.09 (1,906.93)	-434.43*
% of production sold	0.33 (0.47)	0.49 (0.50)	0.17***	0.39 (0.49)	0.38 (0.48)	-0.01	0.29 (0.45)	0.37 (0.48)	0.08**
% of organic fertilizer use	0.73 (0.45)	0.64 (0.48)	-0.09***	0.30 (0.46)	0.48 (0.50)	0.17 ***	0.37 (0.48)	0.44 (0.50)	0.06
% of chemical fertilizer use	0.20 (0.40)	0.26 (0.44)	0.06***	0.22 (0.41)	0.32 (0.47)	0.11***	0.07 (0.25)	0.14 (0.34)	0.07***
% of tractor use	0.56 (0.50)	0.49 (0.50)	-0.07**	0.14 (0.35)	0.34 (0.47)	0.20***	0.22 (0.41)	0.23 (0.42)	0.02
% of paid labor use	0.29 (0.45)	0.43 (0.50)	0.14***	0.30 (0.46)	0.40 (0.49)	0.10***	0.71 (0.45)	0.62 (0.49)	-0.09**
% of access to credit	0.06 (0.23)	0.13 (0.34)	0.07***	0.27 (0.44)	0.31 (0.46)	0.04**	0.07 (0.26)	0.07 (0.26)	0.00

Notes: Standard Deviation in parentheses. All monetary values expressed in 2022 PPP USD. Columns 3, 6 and 9 display the difference in means between groups. Difference unequal to zero if p-value significant at the 99 (***), 95 (**), or 90 (*) confidence level.

In terms of land and production characteristics, households with land titles tend to hold plots that are larger in size, harvest on a larger area, and engage in more irrigation and investment activities compared to those without title. Furthermore, households with land titles exhibit higher levels of commercialization, chemical fertilizer usage, machinery adoption, and access to credit compared to those without titles. It must be noted though that these differences are not uniform across all three countries, and that differences are more pronounced (and statistically significant) in some countries than others. Agricultural production is significantly higher among farmers with land titles in volume and value (though not uniformly so in all countries), indicating a positive association between land tenure security and agricultural outcomes. Nevertheless, agricultural yields do not exhibit this trend.

Overall, this first look at differences between titled and untitled farms would suggest that land tenure security may facilitate greater investment in agricultural inputs and technologies, leading to improved agricultural production and income generation. However, the observed differences are likely biased by the observable and unobservable differences that exist between farmers who have obtained a title and those who have not, which is why the application of rigorous econometric methods is imperative to obtain unbiased estimates of the causal effects of tenure security on agricultural productivity.

5. Empirical strategy

The main purpose of this study is to assess the impact of land tenure security on the agricultural technical efficiency (TE) of smallholder farmers. TE denotes the capacity of agricultural production systems to achieve the maximum feasible output from a given set of inputs and technology (Bravo-Ureta et al., 2006). We concentrate on TE as the principal outcome of interest because it offers a more comprehensive understanding of the relationship between inputs and outputs compared to merely measuring output quantity. To assess the technical efficiency of farm production, we employ a Stochastic Production Frontier (SPF) analysis. As first proposed by Aigner et al. (1977) and Meeusen and van Den Broeck (1977), the SPF model has been used for several decades to estimate the level of technical efficiency of a particular farm relative to an estimated ideal efficiency frontier, as the relationship between the observed and potential production levels of said farm. The SPF models the output of the farm as a function of productive inputs, technical inefficiency, and random error. Since tenure security is not considered a direct farm input and therefore does not appear directly in the production function, it is considered an exogenous determinant of efficiency (Abdul-Salam & Phimister, 2016).

The primary challenge in uncovering the impact of land tenure security on the TE of smallholder farmers then lies in the possibility that certain observed and unobserved characteristics may directly impact a farmer's decision to obtain or pursue a land title. In other words, there exists a potential selectivity bias wherein a farmer's choice regarding inputs into his or her production function may be endogenous, since tenure security not only spurs investments in land and inputs, but such investments may in turn strengthen tenure security (Abdulai et al., 2011; Besley, 1995; Coulibaly, 2022; Lawin & Tamini, 2019). Empirical studies have shown that the more productive the land, the higher the likelihood of titling (Brasselle et al., 2002). Put simply, there is a likelihood that the error component in the selection equation is correlated with the typical random error, leading to selectivity bias that hinders the attainment of consistent and unbiased estimates regarding the causal relationship between land tenure security and TE.

To address this concern, we implement a multi-stage empirical strategy which aims to control for endogeneity stemming from both observable and unobservable differences between titled and untitled farmers, following similar applications employed to obtain unbiased estimates of TE (Asmare et al., 2022; Bravo-Ureta et al., 2006; Bravo-Ureta et al., 2012; Bravo-Ureta et al., 2021;

González-Flores et al., 2014; Lawin & Tamini, 2019; Villano et al., 2015). Firstly, to address selectivity bias stemming from observed farmer characteristics, we employ the PSM method to construct a comparable sample of farmers with and without legal property rights based on observable characteristics. Secondly, we apply a sample selection model proposed by Greene (2010) to this matched sample to correct for selectivity bias due to unobserved variables. Lastly, to address the concern that different production systems will exhibit varying technical efficiency frontiers, we apply the metafrontier approach first proposed by Battese et al. (2004), which enables the estimation of TE within and between each production system. This multi-stage approach therefore effectively addresses endogeneity concerns, enabling the unbiased estimation of technical efficiency and to subsequently evaluate the impact of land tenure security on TE among smallholder farmers.

5.1. Correcting for selectivity bias

5.1.1. Propensity score matching

In order to account and control for observable characteristics that may affect the likelihood of a farmer having legal title and therefore potentially bias our estimates, we employ PSM to limit our sample of untitled farmers such that they resemble titled farmers. This is based on a model of the probability of holding a title, T , conditional on a vector of observed characteristics, X , known as the propensity score: $P(x) = \Pr(T = 1|X)$.

Rosenbaum and Rubin (1983) demonstrated that, under the assumption of conditional independence and presence of common support, matching on the propensity score is as effective as matching on the observed characteristics themselves in achieving balance between the two groups (e.g., holding title and not holding title). Conditional independence implies that the choice to obtain a title is entirely based on observed characteristics. Common support ensures that there exist enough comparable titled and untitled farmers, meaning that a substantial area of overlap can be found for the propensity score distributions of these two groups.

Propensity scores are estimated as a function of several covariates that we expect would affect the likelihood of holding legal title to at least one plot, including characteristics of the household head (age, gender, education, marital status), household size, total area of cultivated land, household off-farm income, asset ownership¹², participation in livestock activities, and regional fixed effects. Matching is estimated separately for each country, employs the 1-to-1 nearest neighbor with replacement method, and imposes the common support condition, following the approach used and recommended by previous studies (Asmare et al., 2022; Bravo-Ureta et al., 2021; González-Flores et al., 2014; Lawin & Tamini, 2019).¹³

5.1.2. Sample selection stochastic production approach

Sample selection bias occurs when there is a correlation between unobservable factors in the production function equation and those in the sample selection equation. Using the stochastic frontier framework, we apply Greene's (2010) bias-correction to address the above-mentioned selectivity problem. The correction comprises two simultaneous equations. First a selection equation and second a SPF function, assuming that unobserved characteristics in the selection

¹² An index, constructed via Principal Component Analysis (PCA), serves as a proxy for productive asset ownership. It encompasses ownership of various agricultural assets, including a plow, sprayer, mill, and others. It allows aggregate several binary ownership characteristics into a single variable.

¹³ It should be noted that some of the above-cited studies have applied nearest neighbor matching without replacement as an alternative matching method; however, since the number of available observations from the untitled group of farmers varied by country case, we opted for the slightly less stringent method with replacement.

equation are correlated with the error term in the SPF function. The specification of this model is as follows:

$$\text{Selection Equation: } d_i = 1[\alpha'z_i + w_i > 0], \quad w_i \sim N(0,1) \quad (1)$$

$$\begin{aligned} \text{SPF function: } & : y_i = \beta'X_i + \varepsilon_i, \quad \varepsilon_i \sim N(0, \sigma_i^2) \quad (2) \\ & : (y_i, X_i) \text{ are observed only when } d_i = 1 \end{aligned}$$

$$\begin{aligned} \text{Error Structure: } & : \varepsilon_i = v_i - \mu_i \quad (3) \\ & : u_i = |\sigma_u U_i| = \sigma_u |U_i|, \quad \text{where } U_i \sim N(0,1) \\ & : v_i = \sigma_v V_i, \quad \text{where } V_i \sim (0,1) \\ & : (w_i, v_i) \sim N_2((0,1), (1, \rho\sigma_v, \sigma_v^2)) \end{aligned}$$

Where d is a binary variable equal to one for farmers with land title and zero for farmers without land title. y is production output of farm i , z is a vector of explanatory variables at the farm level in the stochastic frontier model. w is the normally distributed error term of the selection equation. The model assumes that selectivity bias exists in the form of a correlation between unobserved factors in the selection equation, which are captured by error term w , and unobserved factors in the SPF function, as captured by error term v .

Empirically, the selection equation is estimated using a probit model and represents the likelihood that a farmer will exhibit full property rights as follows:

$$D_i = \alpha_0 + \sum_{k=1}^n \alpha_k \cdot Z_{ki} + \varepsilon_i \quad (4)$$

Where D_i is a binary variable representing the likelihood that the farmer has a formal land title. Z_i is a vector of exogenous variables including socio-demographic characteristics of the farmer and their household, as well as land-specific characteristics, such as land size.

The SPF model will be estimated using a log-linear Cobb-Douglas specification:

$$\log(y_i) = \beta_0 + \sum_{j=1}^n \beta_j \cdot \log(X_{ji}) + v_i - \mu_i \quad (5)$$

Where y_i denotes production output of farmer i , X_i represents a vector of farm level inputs (land, labor, and variable inputs). v_i accounts for purely random factors, and μ_i represents technical efficiency factors.

Unbiased technical efficiency (TE) of smallholder farmers' production is then estimated as a function of the error term μ from the SPF model and represents the ratio of actual output to the output frontier, as follows:

$$TE_i = \exp(-\mu_i) \quad (6)$$

The simultaneous equations (sample selection and SPF equation) are estimated automatically in a routine incorporated in NLOGIT 6 (Greene, 2016). The routine first estimates the parameters in the probit selection equation. α are estimated by maximum likelihood (ML). In the second step, the stochastic frontier model that integrates the sample selection effect is estimated by maximum simulated likelihood (MSL).

5.2. Meta frontier approach

One limitation of the methodology proposed by Greene (2010) lies in the inherent challenge of directly comparing Technical Efficiency (TE) scores between farmers with and without full property rights. This difficulty arises because the estimated TE scores are inherently relative to the specific technologies and frontiers of each group, as noted by Gonzáles-Flores et al. (2014). To overcome this obstacle, we adopt the meta frontier production function approach, which allows for the creation of a common benchmark technology to facilitate a direct comparison between farmers and differentiate between the effect of tenure security on factor use intensity (i.e., impact on technical efficiency) and technological change (i.e., impact on production frontier) (Lawin & Tamini, 2019; Villano et al., 2015). This meta frontier production function can be expressed as:

$$y^* = f(x_i, \beta^*) = e^{x_i \beta^*} \quad (7)$$

Where y^* is the meta frontier output, β^* denotes the vector of parameters such that $x_i \beta^* \geq x_i \beta_j$ and β_j are parameters obtained from each of the group specific frontiers, enabling the estimation of the meta-technology gap ratio (MTR). This ratio represents the highest attainable group output relative to the maximum achievable output of the meta frontier (Villano et al., 2015). In essence, it quantifies the disparity in efficiency attributable to the selection of a specific technology. The MTR lies between zero and one, and is expressed as:

$$MTR = \frac{e^{x_i \beta_j}}{e^{x_i \beta^*}} \leq 1 \quad (8)$$

The technical efficiency of each farmer relative to this meta frontier (MTE) is then calculated as:

$$MTE = TE_j * MTR_j \quad (9)$$

In order to estimate the meta frontier, we use the matched sample and employ the parametric stochastic frontier framework introduced by Huang et al. (2014). This framework comprises two steps consisting of two SFP regressions. First a group specific frontier is estimated as follows:

$$\ln(y_{ij}) = f_j(x_{ij}, \beta^j) + v_{ij} - \mu_{ij}, \quad i = 1, 2, \dots, N_j \quad (10)$$

The meta frontier is then estimated as:

$$\ln \hat{f}_j(x_{ij}, \beta^j) = f_M(x_{ij}, \beta) + v_{iM} - \mu_{iM}, \quad \forall j = 1, 2 \quad (11)$$

Where $\ln \hat{f}_j(x_{ij}, \beta^j)$ is the estimate of the group-specific frontier from equation (10). Since the estimates $\ln \hat{f}_j(x_{ij}, \beta^j)$ are group specific, equation (5) is estimated j times, one for each group, (in our case twice, one for titled and one for untitled farmers). These output estimates from all j groups are then pooled to estimate equation (11).

5.3. Estimation of tenure security impact on technical efficiency

After estimating both the sample selection technical efficiency and the meta frontier technical efficiency, we evaluate the impact of holding legal land title on the unbiased estimates of technical efficiency. This assessment is conducted through the following Tobit regression model:

$$MTE_i = \gamma_0 + \gamma_1 Tenure_i + \sum_{i=1}^n \gamma_2 W_i + \sigma_i \quad (12)$$

In this equation, MTE_i denotes the technical efficiency with respect to the meta frontier of farm-household i . $Tenure_i$ is a binary variable indicating whether the farmer holds formal legal title for at least one parcel. W_i represents a vector of socio-demographic and productive covariates at the farm level. Therefore, γ_1 is the parameter of interest which estimates the (average treatment) effect of tenure security on technical efficiency.

5.3.1. Panel analysis

In the case of Ecuador, we take advantage of the availability of two rounds of data that were collected in the context of SigTierras' impact evaluation and apply a Difference-in-Difference model to estimate the effect of receiving title on technical efficiency. By using this approach, we aim to control for any additional unobservable time trends that may bias causal estimates of the effects of land tenure security on technical efficiency by comparing changes in outcomes over time between farmers who obtained a title in the four years between the collection of baseline and endline surveys, and those who did not.¹⁴

To estimate the technical efficiency relative to the meta frontier, we adopt a similar approach to our cross-sectional analysis. We first estimate group-specific frontiers, and subsequently utilize the predicted outputs to estimate an aggregate frontier. This process is conducted separately for each of the data collection rounds, namely baseline and endline. By doing so, we obtain the estimated technical efficiency measures to be used as the outcome in our Difference-in-Difference model.

The identifying assumption of the Difference-in-Difference model is that technical efficiency of titled farmers would have evolved in a trend parallel to that of untitled farmers in the absence of receiving the title. Though we are unable to test this underlying assumption due to the lack of historic data, we again apply PSM to address potential sources of selectivity bias and to increase the comparability of the groups across a vector of baseline covariates, as described in the previous subsections. The effect of obtaining title on technical efficiency is then estimated for the matched sample as follows:

$$TE_{it} = \beta_0 + \beta_1 \cdot Titled_i + \beta_2 \cdot Post_t + \beta_3 \cdot Titled_i \cdot Post_t + \gamma \cdot X_{it} + \mu_{it} \quad (13)$$

Where TE_{it} (or MTE_{it}) is the outcome of farm-household i in time period t . $Titled_i$ is a binary variable indicating whether the farmer obtained a legal land title in the period between baseline and endline, while $Post_t$ is a binary variable indicating the time period in which the endline was collected. X_{it} is a vector of control variables, and μ_{it} is the error term. The impact is captured by the coefficient β_3 on the interaction between $Titled_i$ and $Post_t$.

5.4. *Pathways of increased productivity*

Economic theory posits several channels through which land tenure security may influence agricultural productivity and efficiency. As described in Section 2, these include the ability to access credit thanks to using land as collateral, reduced transaction costs in a functioning land market, lowered risk of land conflicts, and increased benefits to land investment. In order to shed light on which of these mechanisms may be at play in the relationship between tenure security

¹⁴ Note that our analysis does not use the preassigned treatment and control groups that were created for the impact evaluation of the SigTierras program, given that the program was ineffective at issuing titles. See Section 4.1 for more details.

and technical efficiency, we employ a probit model using the matched sample to assess the impact of land tenure security on some of three of these mechanisms for which data was available, namely credit access, productive land investment, and land conflicts (note that information on a history of land conflicts was not available in the case of Bolivia). All three variables are binary indicators that measure whether a farmer accessed credit or made an invested in their land in the last 12 months, or experienced a conflict related to their tenure within the last five years. The probit model is structured as follows:

$$Y_i = \delta_0 + \delta_1 \cdot Titled_i + \theta + \mu_{it} \quad (14)$$

Where Y_i is the binary variable capturing each of the three mechanisms. $Titled_i$ is a binary variable representing the possession of a land title, with δ_1 capturing the coefficient of interest. θ accounts for country fixed effects, while μ_{it} captures the error term. With the exception of Ecuador, this estimation will only allow us to assess possible correlation between tenure and these mechanisms, since the specification does not permit controlling for unobserved selectivity bias as was possible with Greene's sample selection SPF approach.

6. Results

6.1. Propensity score matching

Our PSM method employs the 1-to-1 nearest neighbor with replacement approach, while adhering to the common support condition. We follow Imbens and Rubin (2015) to select the relevant covariates to the PSM model. We first identify a set of base covariates selected according to their theoretical association with holding a legal title. Here we include total land extension, sociodemographic characteristic of the household head (age, marital status, gender, schooling), total household working members, and regional controls. As a second step we choose from a set of 15 additional variables, including, among others, livestock activity, wealth quintiles¹⁵, and off-farm income. We do this by adding one variable at a time to the logistic regression and calculating the likelihood ratio statistic that tests the null hypothesis that the coefficient on the additional covariates is equal to zero. We do this until the additional variable does not improve the fit of the model. Through our matching procedure, we obtain a sample of 2,986 farmers, comprising 2,118 titled and 868 untitled individuals.

Figure 1 in the Appendix presents the density estimates of the distribution of the propensity scores for titled and untitled farmers for each country, prior to and after matching. As can be seen, after applying PSM, the overlap between the two groups increases significantly, resulting in the reduction of observable selectivity bias in our study sample. Furthermore, Figure 2 in the Appendix demonstrates the reduction in bias achieved through PSM, as measured by the standardized difference of means between the matched and unmatched sample. This standardized bias, before and after matching, is then compared to Rubin's variance ratio. As emphasized by Rubin (2001), the variance ratio of the covariates after matching should approximate one to ensure covariate balance. The figures reveal that matching reduces bias for the samples in all three countries.

¹⁵ Wealth, akin to asset ownership, is represented by an index constructed through Principal Component Analysis (PCA). This index comprises four distinct dimensions: productive assets, non-productive assets (such as TV, fridge, stove, etc.), a dwelling quality index reflecting the quality of materials used for the household's main dwelling's walls, roofs, and floors, and an access to services index, which evaluates the household's access to running water, sanitation, electricity, and gas for cooking.

Table 4: Balance Test Matching Sample

Country	Bolivia	Ecuador	Peru
Variable	(1)	(2)	(3)
Female household head	0.015	0.022	-0.032
Age of household head	-1.034	3.118***	-0.855
Married household head	0.012	0.002	0.03
Native language household head	0.200***	-0.005	-0.037
Number of household members	0.188	-0.008	0.058
Education of household head	-0.705**	-0.181	0.169
Log total annual labor income	-0.417**	-0.324	0.164
Log plot size	0.335***	0.115**	0.191
Log surface area harvested	0.051	0.025	0.063
% of land irrigated	0.078**	0.102***	0.019
% of plots that received investment	0.027	0.012	0.041
% of HH who faced land conflict		0.034**	0.023
Log annual production volume (Kg)	0.586***	0.05	1.037***
Log annual production value (USD)	0.487**	0.358***	0.02
Agricultural productivity (Kg/Ha)	914.673	186.049	260.129
Agricultural productivity (USD/Ha)	-142.78	-128.340**	-528.815**
Productive asset index	0.425***	0.08	0.304**
% of access to credit	0.056**	0.032	-0.02
% of production sold	0.136***	-0.006	0.018
% of organic fertilizer use	-0.068**	0.115***	-0.002
% of chemical fertilizer	0.083**	0.083***	0.052
% of tractor use	-0.039	0.145***	0.015
Number of paired observations	736	1,229	153

Lastly, to test the quality of the matches, we perform t-tests on the mean of relevant sociodemographic and productive variables that we consider may be affected by observable selectivity bias. The results are presented in Table 4 and suggest that some differences in observable characteristics do persist, though have been significantly reduced in comparison to pre-matching differences between farmers with and without land title.

6.2. Stochastic production frontier

Following Bravo-Ureta et al. (2012) and González-Flores et al. (2014) the empirical SPF model uses a Cobb-Douglas functional form given by:

$$Y_i = \beta_0 + \beta_1 \cdot X_i + \beta_2 \cdot Z_i + \beta_3 \cdot R_i + \mu_i + \nu_i \quad (15)$$

Where:

Y_i : the log of total value of farm production expressed in 2022 PPP dollars.

X_i : the log of land extension (in hectares), and variable input expense, labor expense, livestock expense and other expenses, in 2022 PPP dollars.

Z_i : binary variable that accounts for irrigation technology (=1 for farmers that have irrigation)

R_i : Country fixed effects

μ_i : two sided normally distributed error term

v_i : one sided non-negative error term that captures TE.

Table 5 presents the maximum-likelihood estimates of the stochastic production frontier for all specifications discussed in the previous section, ordered from least to most robust: column (1) presents the estimation for the pooled unmatched sample applying the conventional SPF methodology without sample selection; column (2) and (3) present SPF models estimated separately for titled and untitled farmers based on an unmatched sample, but applying the sample selection correction; column (4) estimates the meta frontier from these two specifications; columns (5), (6), (7) and (8) follow the same approach, with the difference of using a matched sample.

The estimates shed light on the relevance of different determinants of production within the agricultural sector in the Andean region. Across all models, the logarithm of expenses pertaining to variable inputs, livestock management, hired and household labor, and other expenses exhibits consistently positive and statistically significant coefficients at the 99% confidence level. This suggests a robust relationship wherein higher expenditures correspond to increased production levels, indicative of a production frontier that exhibits positive yet diminishing returns to individual inputs. Of these factor inputs, the land coefficient figures consistently as largest in magnitude, suggesting that it has the most substantial effect on production output. Furthermore, while the presence of household members appears to have no significant impact on production in the conventional SPF model, it does exhibit a positive and significant effect in all other models. This implies that household members contribute positively to production outcomes, potentially through their labor or other supportive roles. Conversely, the relationship between using irrigation and production is positive and significant in the conventional SPF and metafrontier models. However, the relationship is not statically different from zero for the other sample selection models.

Parameter $\rho(w, v)$ is statistically significant for farmers who hold title and those who do not, suggesting the presence of selection bias on unobserved variables and supporting the use of a sample selection framework to estimate separate SPF models. The likelihood ratio test statistic for the 100% confidence level is 103.92, so that estimates suggest that estimating a separate production frontier for each group of farmers is appropriate. Lastly, we observe that the magnitude of estimated partial input elasticities vary across models, indicating that selectivity bias due to unobserved characteristics is indeed present in the data and thereby confirming the validity of the sample selection SPF approach.

Table 5: SPF Model Estimates

	Unmatched Sample				Matched Sample			
	Conventional SPF	Sample Selection			Conventional SPF	Sample Selection		
	Pooled	Land title	No land title	Meta frontier	Pooled	Land title	No land title	Meta frontier
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Log Land (in Ha)	0.747*** (0.026)	0.602*** (0.026)	0.667*** (0.034)	0.677*** (0.005)	0.730*** (0.033)	0.619*** (0.028)	0.741*** (0.074)	0.619*** (0.000)
Log Input Expenses	0.154*** (0.011)	0.182*** (0.014)	0.126*** (0.016)	0.162*** (0.003)	0.171*** (0.014)	0.176*** (0.014)	0.149*** (0.027)	0.177*** (0.000)
Log Livestock Expenses	0.078*** (0.009)	0.142*** (0.015)	0.054*** (0.014)	0.084*** (0.002)	0.116*** (0.013)	0.133*** (0.015)	0.093*** (0.028)	0.134*** (0.000)
Log Other Expenses	0.050*** (0.015)	0.019 (0.024)	0.066*** (0.025)	0.072*** (0.004)	0.029 (0.018)	0.022 (0.025)	0.06309 (0.051)	0.023*** (0.000)
Log Labor Expenses	0.119*** (0.011)	0.097*** (0.018)	0.139*** (0.019)	0.129*** (0.003)	0.089*** (0.014)	0.093*** (0.019)	0.116*** (0.036)	0.093*** (0.000)
Total HH Members	0.013 (0.059)	0.035** (0.016)	0.042** (0.019)	0.133*** (0.014)	0.029 (0.071)	0.027* (0.016)	0.075** (0.036)	-0.039*** (0.000)
Land Irrigation	0.026** (0.012)	-0.011 (0.090)	0.046 (0.091)	0.033*** (0.003)	0.035** (0.014)	-0.0386 (0.087)	0.198 (0.165)	0.028*** (0.000)
σ_u		3.416*** (0.058)	3.997*** (0.066)			3.388*** (0.056)	3.494*** (0.107)	
σ_v		0.824*** (0.075)	0.903*** (0.051)			0.768*** (0.085)	1.365*** (0.167)	
$\rho(w, v)$		-0.678*** (0.121)	0.905*** (0.045)			-0.619*** (0.235)	0.974*** (0.032)	
Log Likelihood	-11,400.00	-6,269.81	-8,454.59	-2,639.21	-6,211.35	-5,085.60	-2,908.35	-1,941.51
Observations	5,288	2,159	3,129	5,288	2,986	2,118	868	2,986

Notes: Robust standard errors in parentheses. Difference unequal to zero if p-value significant at the 99 (***), 95 (**), or 90 (*) confidence level. All specifications included country fixed effects.

6.3. Technical efficiency

Estimated average technical efficiency scores for all specifications are presented in Table 6 and offer valuable insights into the factor use efficiency of agricultural producers in our sample. In general, levels of technical efficiency are relatively low, ranging between 14 and 28% relative to the stochastic production frontier, depending on the model applied. Across all specifications, the general tendency suggests that holding legal title is associated with a higher level of technical efficiency, and this correlation is maintained at the country level. Specifically, when considering the most robust specification (matched, sample selection and meta frontier), efficiency scores range from 21.05% to 22.38% for farmers with titles, whereas it varies from 14.3% to 17.3% for farmers without titles. On average, we observe an efficiency score differential of 5.85 percentage points (p.p.), ranging from 5.08 p.p. in Peru to 6.75 p.p. in Bolivia. Notably, when considering the unmatched sample, we observe smaller gaps between groups, highlighting the need for bias correction techniques.

Table 6: Technical Efficiency Estimates

	Unmatched Sample				Matched Sample			
	All Countries	Bolivia	Ecuador	Peru	All Countries	Bolivia	Ecuador	Peru
Land Title								
TE Pool	22.78	21.25	23.74	22.80	24.16	23.33	24.63	24.46
TE Sample Selection	21.10	21.09	20.94	22.40	21.27	21.05	21.27	22.38
TE Meta Frontier	21.09	21.08	20.93	22.40	21.27	21.05	21.27	22.38
No Land Title								
TE Pool	22.33	20.39	22.03	23.34	24.05	22.91	23.67	27.13
TE Sample Selection	18.43	16.07	18.48	19.33	19.66	17.90	19.94	21.31
TE Meta Frontier	17.77	15.37	17.28	19.11	15.48	14.30	15.47	17.30

6.4. Impact of land tenure security on technical efficiency

Table 7 presents the results of our estimation of the effect of land tenure status on the meta frontier measure of technical efficiency. The table provides estimates for both the matched and unmatched samples, with and without country fixed effects (FE), encompassing the aggregate regional sample as well as that of individual countries. Across all four specifications at the regional level, land tenure is consistently found to have a positive and statistically significant effect on technical efficiency. As expected, the unmatched sample tends to yield estimates with a downward bias.

Table 7: Tobit Model

Outcome: Meta-Technical Efficiency				
	(1)	(2)	(3)	(4)
A. All Countries				
Farmer holds land title	3.316*** (0.516)	4.244*** (0.567)	5.797*** (0.707)	5.976*** (0.716)
B. Bolivia				
Farmer holds land title	5.712*** (1.059)		6.754*** (1.421)	
C. Ecuador				
Farmer holds land title	3.649*** (0.714)		5.800*** (0.897)	
D. Peru				
Farmer holds land title	3.292** (1.637)		5.083*** (2.090)	
Matching Sample	No	No	Yes	Yes
Country FE	No	Yes	No	Yes
Notes: Robust standard errors in parentheses. Difference unequal to zero if p-value significant at the 99 (***) , 95 (**), or 90 (*) confidence level.				

In the matched sample with country FE, farmers holding land titles demonstrate a technical efficiency approximately 6.0 p.p. higher than their counterparts without titles, indicating a 38.6% difference relative to the average level of farmers lacking titles. When examining each country individually, the effect of land tenure on technical efficiency remains positive across all three countries and specifications. Specifically, in Bolivia, farmers with land titles demonstrate a technical efficiency 6.8 p.p. higher than their counterparts, amounting to a 47.2% difference relative to the average efficiency of Bolivian farmers without titles. In Ecuador, farmers with land titles exhibit a technical efficiency 5.8 p.p. greater than their counterparts, reflecting a 37.4% difference relative to the average efficiency of Ecuadorian farmers without titles. Similarly, in Peru, farmers with land titles exhibit a technical efficiency 5.1 p.p. greater than their counterparts, reflecting a 29.3% difference relative to the average efficiency of farmers without titles

6.5. Panel analysis

Table 7 displays the results of the panel analysis for Ecuador using a Difference-in-Difference model. The base specification includes a dummy variable for title status, a dummy variable for the time period, and their interaction. The second specification incorporates additional household characteristics as controls¹⁶ In both specifications, the findings indicate a negative but statistically insignificant relationship between having attained a land title and the change in technical efficiency over time. It is worth noting that between baseline and endline both groups experience a decline in their technical efficiency levels. Results of the SigTierras impact evaluation confirmed this negative time trend, as results showed that expenses on inputs such as seeds, pesticide, and fertilizer, as well as the value of crop and livestock production declined significantly between baseline and endline across all farms included in the sample (Corral & Montiel, 2022).

¹⁶ Gender, age, years of schooling, marital status, wealth quintiles and regional controls

Table 7 – Difference in Difference Estimates

Outcome: Meta Frontier TE		
	(1)	(2)
Titled	1.500 (1.553)	1.621 (1.546)
Post Period	-3.889** (1.553)	-3.604** (1.557)
Titled * Post Period	-1.165 (2.196)	-1.247 (2.189)
Additional Controls	1.500	1.621
Average TE Scores		
Titled - Baseline		20.92
Titled - Endline		15.86
Untitled - Baseline		19.42
Untitled - Endline		15.53
Notes: Robust standard errors in parentheses. Difference unequal to zero if p-value significant at the 99 (***) , 95 (**), or 90 (*) confidence level.		

6.6. Pathways of increased productivity

Table 8 presents results for probit estimates of the association between holding land title and three potential mechanisms of improved agricultural productivity. At the regional level, results demonstrate a significant association between land title and access to credit and land conflicts: holding title is associated with a 3.3 p.p., or 23%, higher likelihood of having accessed credit in the last 12 months, and a 3.4 p.p., or 47%, higher likelihood of having experienced land conflicts within the last five years. Conversely, it appears that land tenure is positively but statistically insignificantly associated with a higher likelihood of having realized a productive investment in land within the last year

Table 8: Probit Model – Mechanisms

Dependent Variable:	Access to Credit		Productive Investment		Land Conflicts	
	(1)	(2)	(3)	(4)	(5)	(6)
	Coef.	Margin	Coef.	Margin	Coef.	Margin
A. All countries						
Farmer holds land title	0.120** (0.060)	0.033** (0.017)	0.105 (0.069)	0.021 (0.014)	0.170** (0.081)	0.034** (0.016)
B. Bolivia						
Farmer holds land title	0.456*** (0.103)	0.077*** (0.018)	0.241*** (0.078)	0.073*** (0.023)		
C. Ecuador						
Farmer holds land title	0.098 (0.167)	0.031 (0.052)	0.525** (0.256)	0.060** (0.030)	-0.366** (0.220)	-0.057** (0.034)
D. Peru						
Farmer holds land title	-0.134 (0.212)	-0.02 (0.032)	0.267 (0.214)	0.041 (0.033)	0.241 (0.257)	0.024 (0.026)
Notes: Robust standard errors in parentheses. Difference unequal to zero if p-value significant at the 99 (***) , 95 (**), or 90 (*) confidence level.						

Upon closer examination of individual country contexts, distinct patterns emerge. In Peru, none of the tested pathways attained statistical significance, which may possibly be attributed to the fact that, on average, farmers in the sample obtained their title 21.5 years ago on average, so that any effects through these pathways would have occurred prior to our measurement of them within the last year (five years for land conflict). Conversely, in Ecuador, holding title to agricultural land significantly increased the likelihood of having realized a productive investment in land within the last year by 6.0 p.p., while also reducing the likelihood of land conflicts by 5.7 p.p.. No significant association between tenure and credit access is found. In Bolivia, possessing a land title is robustly associated with a 7.7 p.p. increase in access to credit, as well as a 7.3 p.p. increase in the probability of committing a productive investment in the farmland.

7. Conclusions

To our knowledge, this paper constitutes the first study to examine the effect of land tenure security on agricultural technical efficiency in the Latin American context. As such, the study provides important insights into the impact that holding legal land title can have for smallholder farmers' production decisions to increase the efficient use of farming inputs, levels of production and productivity, in the context of the Andean countries Bolivia, Ecuador, and Peru. The wealth of the available data makes this a unique opportunity to better understand whether the oft expected link between tenure security and farm productivity hold for a region in which smallholder farming continues to exhibit low levels of agricultural productivity, and land tenure insecurity is higher than in any other region in the world.

In order to control for the existence of selectivity bias in our cross-sectional data from both observable and unobservable factors, we jointly apply propensity score matching and a sample-selection correcting stochastic production frontier model first proposed by Greene (2010) for a sample of 5,288 titled and untitled farmers. We further estimate meta frontiers to allow for a direct comparison between the productivity levels of farmers who do and do not hold title.

Our results confirm the existence of selectivity bias for both the titled and untitled farmer groups, so that our most robust specification will render the most consistent and unbiased estimates of technical efficiency. Of all inputs to production, land has the most sizeable effect on production output. On average, technical efficiency scores are higher among titled than untitled farmers, both at the regional level as well as within individual countries, though technical efficiency levels are generally low, estimated to be within the lowest tercile of possible technical efficiency scores relative to the meta frontier.

The impact of holding legal land title on technical efficiency is positive and statistically significant at the regional level, and on average holding title is estimated to increase technical efficiency by 6.0 p.p., or 38.6% relative to the average TE score of farmers lacking title. These results run counter to findings from a similar study conducted by Lawin and Tamini (2019) for the case of Benin, who find that untitled smallholder farmers experienced consistently higher technical efficiency scores and productivity levels than those who held a title. Our findings are however in line with previous work by Coulibaly (2022), who found a positive effect of land tenure security on agricultural productivity for Burkina Faso.

When examining the relationship for each country, we find that the positive and significant impact holds for all three countries, though the result for Ecuador does not maintain its statistical significance when applying a more rigorous panel analysis. Lastly, we are able to assess the association between land tenure and possible pathways towards improvements in productivity, and find that for the regional sample, holding legal title is associated both with higher likelihood of accessing credit and experiencing land conflicts, though the significance and relevance of each

pathway vary by country. In the case of productive investments, we only find a positive and significant relationship in Bolivia and Ecuador.

Overall, these results contribute to growing evidence that improving tenure security enhances agricultural efficiency and productivity, though the exact relationship between the two will depend on the country context-specific market barriers that inhibit efficient use of factor inputs, and whether the prevalent land regime enables farmers who hold title to effectively overcome these barriers. Of the three countries in our study, Bolivia proved to exhibit the most robust link between tenure security and productivity, which may be attributed to the fact that the country has made large strides in the last thirty years to regularize, title and register all rural property, so far having achieved titling for 92% of all private rural land in the country. As a result, land markets appear to function more efficiently, with the number of market transactions having increased by 10% between 2018 and 2019 (IDB, 2024). By establishing a land regime in which a majority of smallholder farmers have access to a legal title and recourse in the case of land conflicts, a perception of heightened tenure security is likely enabling farmers to make productive decisions that will reap benefits in the medium- to long-term and sustainably increase productivity.

In contrast, though Ecuador has undertaken ambitious land regularization efforts, progress has stalled and left a significant share of rural farmers in a situation of tenure insecurity. The Sigtierras program aimed to regularize tenure nationwide, but only accomplished creating and issuing cadastral maps to farmers, a step short of issuing legal title, due to the complexities of registering title in the country's legal framework. We therefore posit that holding title alone is not enough to significantly improve productivity levels in a context where a large share of farmers remains to be titled, and the legal and regulatory framework of the national land regime still requires significant strengthening to function efficiently. To realize the full potential of tenure security impact on productivity gains in the agricultural sector, land regularization efforts must focus on updating the legal and regulatory frameworks within which land titles are conferred so that land transfers are efficient and legal recourse for conflict resolution is reliably and easily accessible. Policymakers should continue to advocate for prioritizing comprehensive land regularization as a means to enhancing agricultural productivity levels and food security among smallholder farmers.

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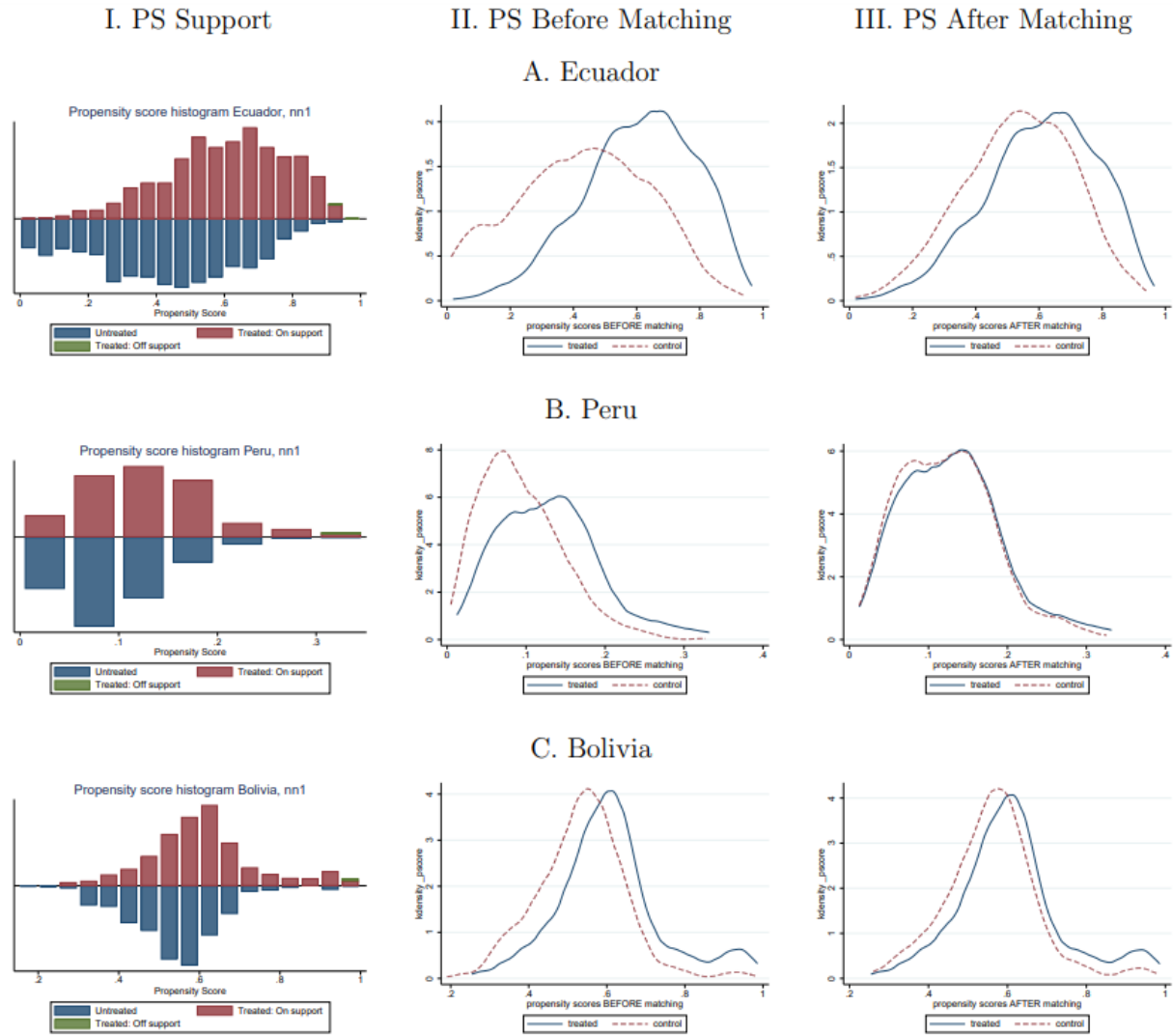
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Appendix

Figure 1: Distribution of propensity scores with and without PSM



Notes: Matching covariates include Household head characteristics (gender, native language, age, marital status, years of schooling), Household Characteristics (total members, wealth quintile, access to credit, participation in non farm labor) and productive characteristics (total land extension and participation in livestock activities)

Figure 2: Balance of Covariates before and after Matching – Bolivia

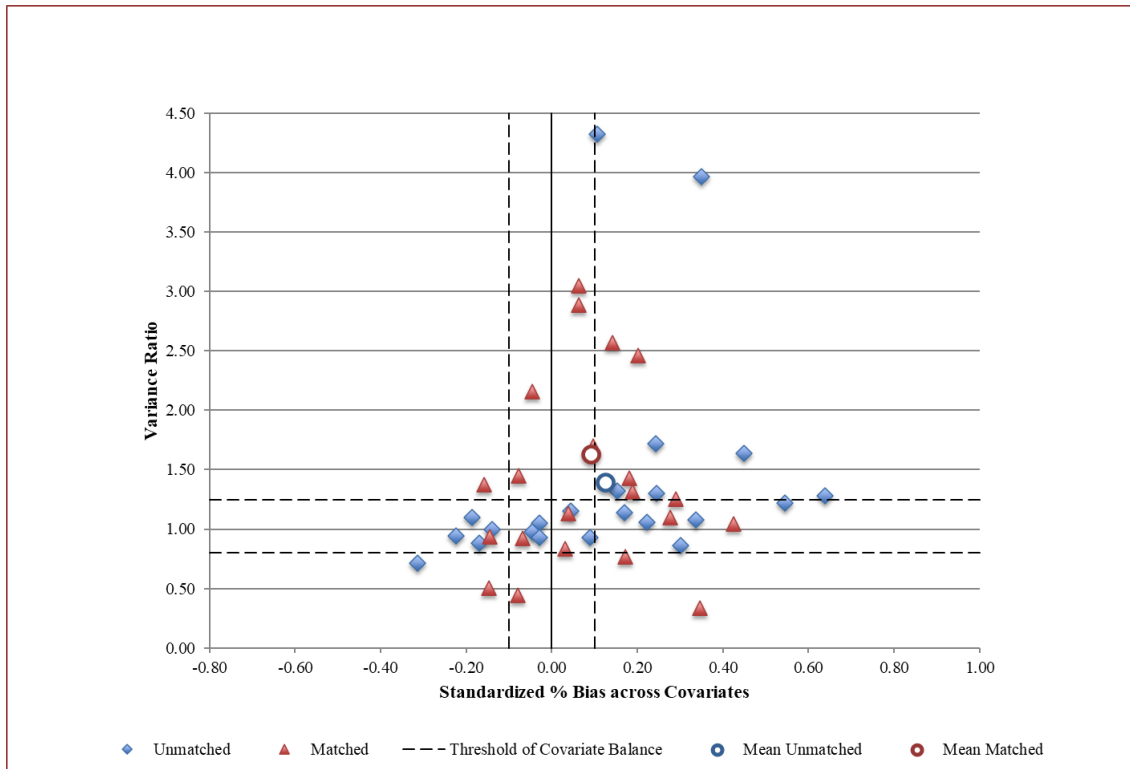


Figure 2: Balance of Covariates before and after Matching – Ecuador – Cont.

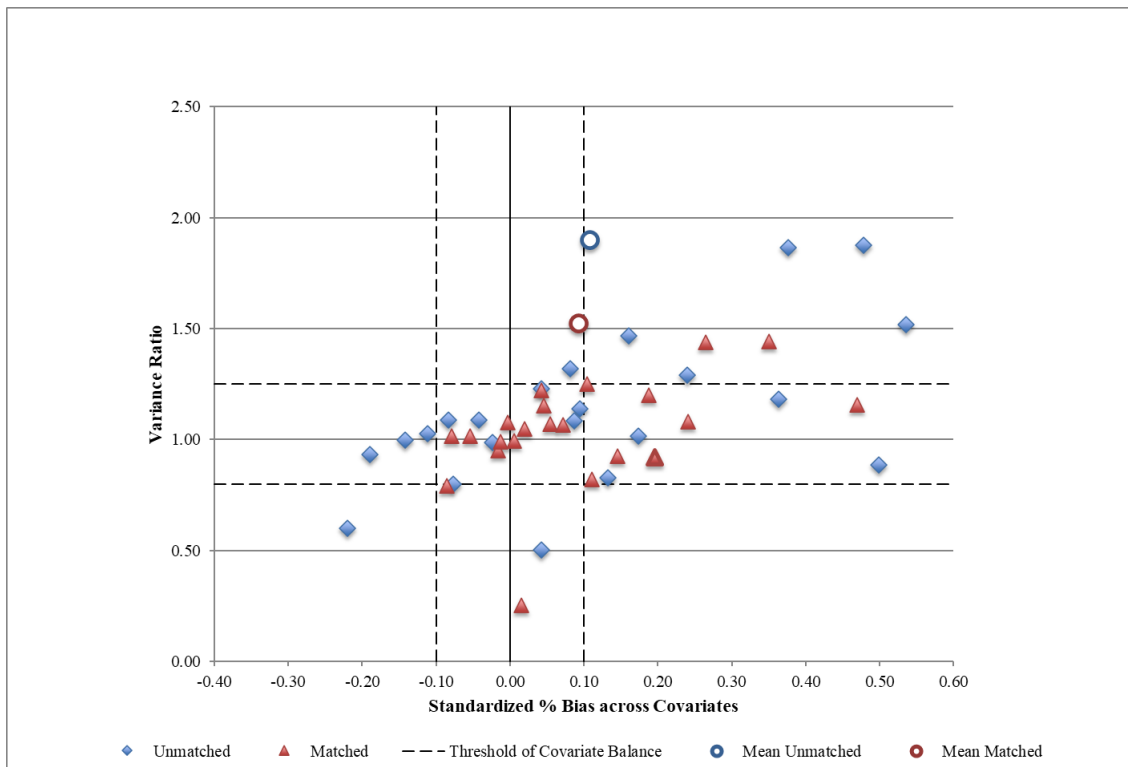


Figure 2: Balance of Covariates before and after Matching – Peru – Cont.

