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Total Factor Productivity, Deforestation, and Voluntary Sustainability Standards: Evidence from Rwandese coffee farmers

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ABSTRACT

Increasing food demand will most likely be met with agricultural intensification and land clearing, exacerbating environmental consequences associated with food supply. The mechanisms and trade-offs between agriculture and the environment are heterogeneous and not well understood, yet key to enhance food production while safeguarding the environment, ensuring a dual purpose of food systems. This study examines the relationship between voluntary sustainability standards (VSS) and Rwandese coffee farmers' technical efficiency and productivity while exploring the mechanisms behind potential trade-offs and synergies between certification, productivity, and forest protection. Using cross-sectional farm-level data of 842 coffee farmers in Rwanda, we measure the effect of VSS on technical efficiency and an enhanced vegetation index (EVI) reflecting vegetation health and density around the farm. We combine a stochastic frontier analysis controlling for sample selection bias with mediation analysis. Our analysis shows that certified farmers exhibit greater technical efficiency levels than non-certified farmers. We can attribute this to better farm management, leading to 19% and 4% increases in their productivity and technical efficiency, respectively. Our analysis also suggests that certifications lead to higher enhanced vegetation index scores in and around the coffee plots, which we attribute to the regulatory mechanisms associated with certification. We conclude that VSS can enhance coffee production while safeguarding the environment and being a valuable component of a more comprehensive rural development program.

KEYWORDS: vo*luntary sustainability standards, coffee, technical efficiency, forest quality, Rwanda*

JEL codes: D22, D24, Q12, Q15, Q23, Q24, Q15, Q18,Q56, O13

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1 Introduction

Projected human population growth and the expected rise in per capita income require increasing agricultural production to meet increasing food demand. This boost in agricultural production will be driven by agricultural intensification, land clearing, or both (Tilman et al. 2011). Nevertheless, the intensification of agricultural practices and the expansion of agricultural land may exacerbate environmental degradation associated with food production, particularly rainforest loss (Laurance et al. 2014; Lewis et al. 2015; Jayathilake et al. 2021). The trade-offs between agricultural development and the environment are highly heterogeneous and depend on the production systems, yet require a comprehensive understanding to enable food systems with a dual purpose: increasing food production while safeguarding the environment.

Voluntary sustainability standards (VSS or certifications hereafter) are a market-based instrument that aims to promote sustainability by mitigating social and environmental externalities from agricultural production systems (Swinnen 2016) by establishing a set of guidelines that farmers must follow. In return, farmers receive an additional payment for their production, commonly referred to as premiums (DeFries et al. 2017). These guidelines vary according to the certification scheme but primarily focus on sustainable agricultural practices, environmental protection, and socioeconomic conditions. However, whether VSS successfully support farmers in increasing their production while safeguarding the environment remains unanswered.

This paper estimates the effect of voluntary sustainability standards on agricultural productivity and deforestation among coffee producers in Rwanda. We first analyze whether the adoption of VSS enhances agricultural productivity and technical efficiency in coffee production. Second, we test whether VSS improve vegetation health and density at the landscape level. Third, we determine the underlying mechanisms, for instance, improvements in agricultural productivity, through which certification may affect vegetation health and density.

Previous research on coffee production suggests that voluntary sustainability standards can increase agricultural production (Jena et al. 2017; Beuchelt and Zeller 2011). Likewise, several studies suggest that VSS can lead to on-farm environmental improvements (Meemken et al. 2021). Few studies have investigated the effect of VSS on deforestation or tree diversity, suggesting the potential for overall positive outcomes (Hardt et al. 2015; Haggar et al. 2015; Takahashi and Todo 2017; Tscharntke et al. 2015; Rueda et al. 2015). Nevertheless, the effect of VSS on environmental and biological indicators at a landscape level remains uncertain due to its limited evidence (Meemken et al. 2021). While some studies examined either the influence of sustainability standards on socioeconomic indicators or the impact on environmental outcomes, the potential trade-offs between socioeconomic and environmental indicators remain relatively unexplored (Haggar et al. 2017; Vanderhaegen et al. 2018; Garrett et al. 2021; Gather and Wollni 2022), especially the relationship between agricultural productivity growth and deforestation.

Our work offers three main contributions to the existing literature. First, previous studies on coffee production suggest that VSS may increase agricultural productivity, yet the specific sources of agricultural productivity growth under VSS are unclear. Our paper helps to expand the scarce empirical research examining how certifications affect farmers' technical efficiency (TE) and technical change (TC). Second, although previous research on the effect of VSS on deforestation and tree diversity hints at positive outcomes, the evidence on the environmental impact of VSS at the landscape level is still very limited. Our paper offers additional evidence on the effect of certifications on vegetation health and density at a landscape level. Finally, the potential trade-offs between socioeconomic and environmental indicators are relatively unexplored, especially the relationship between agricultural productivity growth and deforestation. Our last contribution is to provide evidence of the relationship between productivity growth and vegetation density when farmers adopt certifications.

Our study relies on a stratified random sample from certified and non-certified coffee farmers in Rwanda, collected between November 2022 and January 2023 in Western and Southern Province. We first estimate technical efficiency using stochastic frontier analysis with sample selection correction (Greene 2010) and a meta-frontier analysis to account for technological differences across groups. We then apply an instrumental variable (IV) approach to evaluate the effect of VSS on vegetation density and health. To control for additional time-invariant heterogeneity, we incorporate a lagged outcome variable for vegetation health and density, which confirms that certified farmers were not located in greener areas before certification. Finally, through a mediation analysis, we explore the underlying processes by which certifications influence vegetation health and density.

Our results suggest that voluntary sustainability standards serve a dual purpose in Rwandan coffee production systems, enhancing production levels while also slowing down the degradation of vegetation health and density. First, the productivity analysis results show that VSS increase TE, coffee output, and coffee tree productivity. Second, the results of the IV analysis indicate that areas with certification activity experience slower losses in vegetation health and density than their counterparts. Finally, our mediation analysis shows that the effect of VSS on vegetation health and density is not mediated by increased coffee output and technical efficiency but is more likely due to regulatory mechanisms associated with certification in Rwanda.

We organize the paper as follows. The subsequent Section introduces a conceptual framework and provides a contextual background on coffee production in Rwanda. Our data and methodology are detailed in Section 3. Section 4 presents and discusses our findings. We conclude the paper in Section 5.

2 Background

2.1 Conceptual framework

We present our conceptual framework in this Section and illustrate it in Figure 1. Previous research on coffee production suggests that voluntary sustainability standards can potentially increase agricultural production (Jena et al. 2017; Beuchelt and Zeller 2011). However, the pathways by which VSS enhance agricultural production have not been investigated, and comprehending these mechanisms is crucial for formulating effective policy measures. Growth in agricultural productivity can arise from technological change (TC) and technical efficiency (TE) improvements (Bravo-Ureta et al. 2007). Technological change contributes to productivity growth as new technologies increase the maximum potential output (Coelli et al. 2005). Higher levels of technical efficiency are achieved when a farm produces more output due to better management with the same level of inputs (Bravo-Ureta et al. 2007).

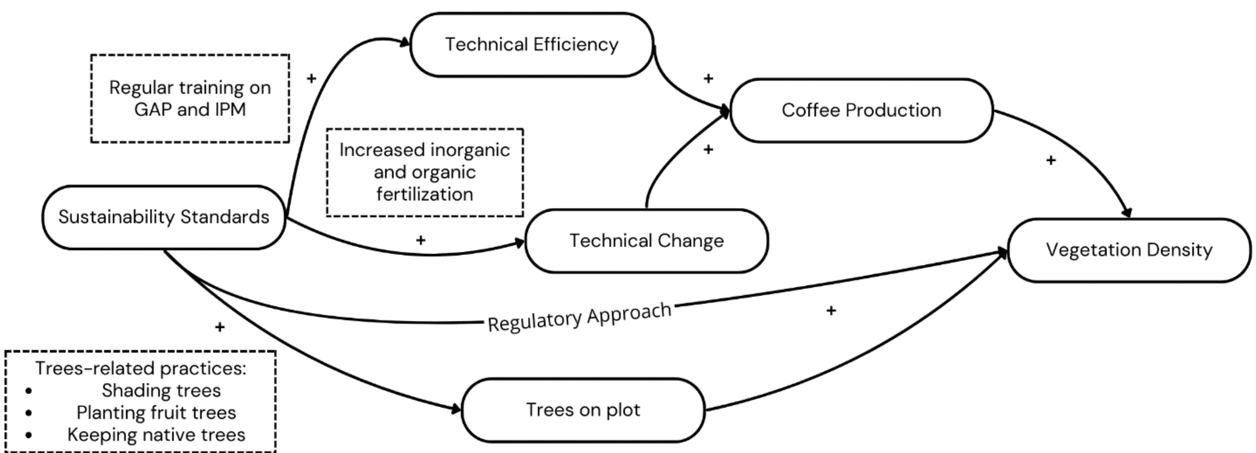

Figure 1: Conceptual framework on the impact of VSS on Vegetation Density and Health

We hypothesize that VSS positively affect technical efficiency and technological change due to the type of practices and technologies they promote, leading to higher coffee output. For example, they encourage ongoing training on integrated pest management (IPM), pruning, and soil conservation. Training is inherently associated with farmers' managerial ability and, consequently, with farmers' technical efficiency. Moreover, when chemical fertilizers are scarce, certified farmers were observed to invest more heavily in chemical fertilization (Jena et al. 2017) and increase organic fertilization practices (Beuchelt and Zeller, 2011). These are some of the practices that can potentially lead to technological change.

We also hypothesize that certifications lead to forest conservation because they affect tree cover and vegetation density at the landscape level. A potential mechanism refers to VSS requiring a minimum proportion of shade trees on the coffee plot while prohibiting the removal of native trees (Café Practices

2016; Rainforest Alliance 2023). Therefore, certifications should also affect tree cover and vegetation density at a landscape level by promoting tree-related sustainable practices on the coffee plots. Another mechanism is improving agricultural productivity through technical efficiency and technological change improvements. While the interplay between agricultural productivity growth and deforestation is complex and context-dependent, there are two main theories that have been discussed in the literature: Borlaug's hypothesis and Jevon's paradox (Villoria et al. 2014). The former suggests that increasing agricultural productivity alleviates the strain on agricultural land to meet rising food demand (Borlaug 2007), while the latter suggests that higher agricultural productivity increases the opportunity costs of conservation, potentially leading to land expansion (Angelsen et al. 2001). Empirical evidence supports Borlaug's hypothesis, showing that increasing agricultural productivity is land-sparing in the long run at a global level (Balmford et al. 2005; Balmford et al. 2018; Feniuk et al. 2019; Folberth et al. 2020; Phalan et al. 2014; Villoria 2019). Although most studies focus on technological change rather than technical efficiency, recent local evidence in Indonesia suggests that increasing productivity through improving technical efficiency is also land-sparing (Dalheimer et al. 2021). Nevertheless, Hertel et al. (2014) indicate that agricultural productivity alone cannot drive or inhibit land use expansion. Instead, this relationship is complex and, thus, should be defined at a local level considering local institutions.

Previous evidence suggests that stronger local institutions, namely strong enforcement systems and land tenure security, are associated with lower deforestation (Robinson et al. 2014; Moreira-Dantas and Söder 2022; Pacheco and Meyer 2022). Thus, we hypothesize that an important mechanism by which VSS protect forests refers to VSS's capacity to serve as a private regulatory instrument and, thus, their capacity to strengthen institutions. This is because they include in their guidelines that production systems cannot expand into natural forests or other natural ecosystems (Rainforest Alliance 2023; Café Practices 2016), promote the conservation and restoration of areas with conservation value outside the certified farm (Rainforest Alliance 2023), and implement a control system of compliance.

2.2 Coffee production in Rwanda

Coffee plays a crucial role in the Rwandese's national economy, contributing substantially to foreign currency earnings and the economic development of rural areas, serving as a cash crop for farmers (NAEB 2023). Approximately 400,000 smallholder farmers depend on coffee cultivation and manage roughly 42,000 hectares. Despite the coffee industry's significance in Rwanda, its productivity stalled in 2004/2005, currently exhibiting one of the lowest productivity rates in Eastern Africa (International Coffee Organization 2015). Low coffee productivity in Rwanda and East Africa is attributable to environmental and institutional factors, as well as poor farm management (Ngango and Kim 2018; AgriLogic 2018). For example, approximately one-fourth of coffee trees in Rwanda are over 30 years old, and the aging farmers often lack the means and motivation to renew their coffee plantations (NAEB 2017). Moreover, farmers do not implement good agricultural practices (GAPs), mainly because of a lack of incentives and extension (AgriLogic 2018). Finally, the lack of proper fertilizer application has significantly reduced volume growth and quality improvement. In this last matter, the National Agricultural Export Board of Rwanda (NAEB) and the Coffee Exporters and Processors Association of Rwanda (CEPAR) have jointly attempted to tackle this issue by supplying agrochemicals to coffee farmers (NAEB 2017).

The coffee harvesting season in Rwanda stretches from March to July. Coffee harvesting is a labor-intensive task (Macchiavello and Morjaria 2022). For fully washed coffee, farmers send coffee cherries to coffee washing stations (CWSs) within six hours of their harvest. The Rwandese government has implemented a zoning policy[1], assigning all coffee farmers within a specific geographic zone to one CWS. This policy obliged farmers to sell their coffee production only to their designated CWS, prohibiting sales or purchases outside these zones and designations. The final product of the CWS is green beans, which are either exported (96-98%) or sold on national markets (2-4%) (AgriLogic, 2018). Alternatively, farmers can process coffee cherries on-farm, obtaining a semi-washed product in the dry mill that they can sell on international markets. Although fully-washed coffee is of higher and more consistent quality and is associated with premium prices on global markets (Blouin and Macchiavello 2019), home processing allows farmers to store coffee and sell it when it is more convenient (Macchiavello and Morjaria 2022).

Sustainability standards have been present in Rwanda since the early 2000. However, since 2014, the quantity of certified coffee has grown (AgriLogic 2018). The predominant standards in Rwanda are FairTrade, Organic, Rainforest Alliance (AgriLogic, 2018), and Café Practice. Sustainability standards require the traceability of the product; therefore, only fully washed coffee is certified in Rwanda. Certification takes place at the level of the CWSs, which are the certificate holders, and they have to implement certification requirements with the farmers assigned to them. Due to the zoning policy, all farmers assigned to a certified CWS need to comply with the certification's requirements, participate in regular training and may be subject to audits by the certification body.

3 Methodology

3.1 Data

This paper uses farm household survey data from a stratified random sample of coffee farmers in Rwanda, conducted between November 2022 and January 2023. The survey was georeferenced and captures information on household demographics, coffee production in the most productive coffee plot, agricultural production, and general household welfare and socioeconomic conditions. We use data from 842 farm

[1] The zoning policy in Rwanda was implemented in 2016 and lifted in June 2023.

households from 2 provinces and five districts in the Rwandese coffee belt, more precisely, in Huye, Rusizi, Nyamasheke, Karongi, and Rutsiro, to capture variations in coffee production across regions. We first randomly selected certified and non-certified coffee washing stations in each district, which we identified from a list provided by local authorities. Subsequently, we randomly selected farmers from a complete list provided by each CWS. The certification schemes in the area were Rainforest Alliance, Fairtrade, Café Practice, and Organic. A CWS can hold a single or multiple certifications. For this paper, we consider those farmers who supply coffee to a CWS with at least one certification scheme as certified. The total sample includes 515 certified farmers and 327 non-certified farmers.

3.2 Analytical and Empirical Framework

We address our research questions using a three-step estimation strategy consisting of stochastic frontier analysis (SFA), instrumental variables (IV), and mediation analysis (MA). The first research question requires investigating whether VSS improve technical efficiency and coffee productivity. To do so, we follow Greene (2010) to estimate farmers' technical efficiency while addressing self-selection bias. We account for potential technological differences across certified and non-certified farmers by combining the stochastic frontier analysis with a meta-frontier analysis. We follow the methodology proposed in Huang et al. (2014) to estimate our meta-frontier and generate technology gap ratios for certified and non-certified farmers. For our second research question, we apply an instrumental variable (IV) approach to evaluate the effect of VSS on vegetation density and health. Moreover, we use lagged vegetation health and density before the start of certification activities to control for additional time-invariant heterogeneity. Finally, we use a mediation analysis to combine our previous analyses and explore the underlying mechanism by which certifications influence vegetation health and density.

3.2.1 Stochastic frontier analysis: Comparing farmers' productivity and technical efficiency across certified and non-certified farmers

Stochastic frontier analysis (SPF) is a prominent approach to analyze productivity and efficiency across different industries (Ray et al. 2022). We can specify the standard stochastic frontier model for a production frontier as:

$$Y_{jit} = f_t^j(X_{jit})e^{V_{jit}-U_{jit}}, \qquad j = 1, \dots, N; \;\; i = 1,2, \dots, N; \;\; t = 1,2, \dots, T \qquad (1)$$

Where Y_{jit} represents the output and X_{jit} the input vectors for a period *t* and the farmer *i* that belong to the group *j*. The U_{jit} term captures inefficiency as a reduction from maximal output dictated by the production technology, and it is assumed to have a half-normal distribution u~$N(u,\sigma_u^2)$, while the V_{jit} term captures stochastic shocks, and it is assumed to have a normal distribution v~$N(0,\sigma_v^2)$. Both terms are assumed to be independent and identically distributed. The technical efficiency of a farm *i* can be calculated as follows:

$$TE_{it}^{j} = \frac{Y_{jit}}{f_t^j(X_{jit})e^{-V_{jit}}} = e^{-U_{jit}} \qquad (2).$$

Conventional SFA assumes the absence of unobserved heterogeneities across groups of certified and non-certified farmers (Greene 2010), and certified and non-certified farmers to operate under the same technology (Orea and Kumbhakar 2004).

We follow the methodology proposed by Greene (2010) to deal with the bias from unobserved heterogeneity. This approach combines a self-selection bias model with a stochastic frontier model. It suggests that the unobservable part of the former is correlated to the composed error of the latter. Greene (2010)'s methodology is an extension of the framework proposed by Heckman (1979) for linear models that is adaptable to the non-linear nature of the stochastic frontier approach, and it can be described as follows:

Sample selection model: $d_i = 1[\alpha' z_i + w_i > 0],\ \ w_i \sim N(0,1)$ (3)

Stochastic frontier model: $y_i = \beta' x_i + \varepsilon_i, \quad \varepsilon_i = v_i - u_i$ (4)

$$u_i = |\sigma_u U_i| = \sigma_u |U_i| \text{ where } U_i \sim N(0,1)$$

$$v_i = \sigma_v V_i \text{ where } V_i \sim N(0,1)$$

$$(w_i, v_i) \sim N_2[(0,0),(1, \rho\sigma_v, \sigma^2{}_v)].$$

As the model is estimated twice, once for certified and once for non-certified farmers, d_i is a binary variable that equals 1 for the group of farmers for whom the model is estimated; z_i is a vector of observable variables included in the sample selection model that can influence the decision to get certified; w_i is the unobservable part of the selection model, which is correlated with the stochastic error term in the production frontier v_i. The vector z_i includes the gender of the household head, age of the household head, literacy of the household head, main occupation of the household head, years of farming experience of the household head, the size of the household, the income coming from all activities not related to coffee production, the ownership of the land, the proportion of land under agriculture, the access to financial institutions, the participation in a cooperative, and distance to the closest agricultural market.

For our production functions, we considered the two most common functional forms frequently employed in efficiency analysis (Bravo-Ureta et al. 2007): Cobb-Douglas (CD) and translog (TL). Results of maximum likelihood ratio tests indicate that TL production functions are the most suitable functional form to represent the production technology of certified and non-certified farmers. The group TL stochastic production frontiers for certified (5) and non-certified farmers (6) can be defined as:

$$y_i = \beta_0 + \sum_{j=1}^{n} \beta_j x_{ij} + \frac{1}{2}\sum_{j=1}^{n}\sum_{k=1}^{n} \beta_{jk} x_{ij} x_{ik} + v_i - u_i \qquad (5), \text{ and}$$

$$y_i = \beta_0 + \sum_{j=1}^{n} \beta_j x_{ij} + \frac{1}{2}\sum_{j=1}^{n}\sum_{k=1}^{n} \beta_{jk} x_{ij} x_{ik} + v_i - u_i \qquad (6).$$

Where y_i represents the log of the output of the i[th] farmer; x_{ij} represents the log of the quantity of the j[th] input for the i[th] farmer; β represents the unknown parameters to be estimated; and v and u are the elements of the composed error term. The output in our function is the total kilograms of coffee produced during 2022 in the most productive coffee plot. The inputs in our model are the size of the most productive coffee plot in hectares, the density of coffee trees (trees per hectare), the age of the coffee plantation in years, fertilizer, insecticide, and fungicide use in USD, total labor (number of working days), and the number of shade trees in the coffee plot. The dummy variables in our model control for the implementation of organic practices and the province. Additional dummies were included in the function to control for the inclusion of zero values for fertilizer, insecticide, fungicide, and shade trees (Battese 1997).

In the model proposed by Greene (2010), α and β are parameters to be estimated using a simulated maximum likelihood estimation (SMLE). We estimated all the models using NLOGIT6S and RStudio. Finally, the coefficient ρ measures the correlation between the w_i and v_i. A statistically significant ρ estimate suggests the existence of self-selection bias due to unobservable characteristics that influence both certification status and productivity outcomes.

The main shortcoming of the approach specified above is that TE for the group of certified and non-certified farmers is calculated with respect to their own group's frontier. Therefore, it does not allow for a direct comparison of TE scores between the two groups (González-Flores et al. 2014). To overcome this problem, we follow Huang et al. (2014), and estimate a stochastic meta-frontier (SMF) production function. The SMF production function $f_t^M(X_{jit})$ envelops both certified and non-certified group frontiers $f_t^j(X_{jit})$. This approach requires first the estimation of the individual group frontiers as specified in equation 1 (or equation 4 in the presence of selection bias) and then pooling the predicted output of each frontier with the corresponding input data to estimate the SMF. Then, the meta-frontier can be defined as:

$$ln\hat{f}_t^j(X_{jit}) = lnf_t^M + V_{jit}^M - U_{jit}^M, \quad \forall\, i,t,j = 1,2,\dots,J \qquad (7)$$

Where $ln\hat{f}_t^j(X_{jit})$ is the predicted output of each group-specific frontier from the first step and lnf_t^M the corresponding inputs vector. Therefore, the technology gap ratio (TGR) and the meta-frontier technical efficiency (MTE) can be defined as:

$$TGR_{it}^j = \frac{f_t^j(X_{jit})}{f_t^M(X_{jit})} \qquad (8)$$

$$MTE_{jit} = TGR_{it}^{j} * TE_{it}^{j} \quad (9)$$

While TGR focuses on measuring the gap between the technology used by specific farmers and the best available technology, meta-technical efficiency evaluates how close a farmer is to the best performer in the whole group of farmers, taking into account both the efficiency of input use and the level of technology. Following our conceptual framework, a change in TGR represents technological change (TC), and a change in TE represents technical improvement (or a decline).

3.2.2 Measuring changes in vegetation health and density

To measure vegetation health and density, we rely on vegetation indices. Vegetation indices provide a combined assessment of leaf area, chlorophyll levels in leaves, canopy coverage, and canopy structure, ultimately representing the overall "greenness" of the area (Didan and Barreto Munoz 2015; Glenn et al. 2008). This type of indicator derives from the fact that chlorophyll in plants absorbs red wavelengths, while a low canopy density results in near-infrared wavelengths (Tucker 1979). Vegetation indices are usually low in areas with sparse vegetation cover (deserts), intermediate in places like savannas, and reach the highest values in tropical forests (Huete et al. 2010).

The two most often used vegetation indices are the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). Nonetheless, in regions with abundant vegetation, such as tropical areas, NDVI reaches a saturation point (Huete et al. 2002). Therefore, we use the EVI for our analysis, which was developed as an index to perform better than NDVI in high-dense biomass regions and reduce the atmospheric influence in the analysis (AgriLogic 2018; Huete et al. 2002; Didan and Barreto Munoz 2015). However, we use NDVI values for robustness checks.

As we georeferenced each coffee plot, we retrieved for December 2022 the mean EVI value within a 500-meter radius of each coffee plot using MODIS-NASA data, which provides a spatial resolution of 250 meters by 250 meters. A potential first concern regarding our outcome variable is its correlation with certifications, meaning that farmers who got certified may have been already in areas with greater vegetation density before getting certified. Another issue arises because forests in a radius of 500 meters around the coffee plot (landscape) may be affected by other actors than the farmer, confounding the effect of certifications on vegetation health and density. The third concern is potential baseline differences not associated with forests across farmers and groups within this radius, which can affect the EVI measures and confound the effect of certifications as well.

To address our first concern, we explore the EVI value within a 500-meter radius for every coffee plot for the period before the certification activity starts in our sample (2003). We calculate the average EVI value for three years to control for potential particularities within each year. To control for our second concern, we rely on the zoning policy to extend our analysis to a landscape level. Under the zoning policy, each farmer is located within a radius of 5 kilometers of their designated CWS. Moreover, as previously mentioned, the farmer is certified if the CWS is certified. Consequently, we delineate the area of influence for each CWS using a convex hull method, forming a polygon encompassing the outermost farmers from each CWS in our sample. Subsequently, we compute the average EVI for the entire area surrounding each CWS. While this methodology enables us to capture values at a landscape level, we only have 39 data points due to the limited number of CWS (25 certified and 14 non-certified). Thus, we employ these values only for robustness checks. Finally, to address our third concern, the potential baseline differences not associated with forests, we employ the difference of EVI for 2020-2022 and 2001-2003 (a lagged variable) as the outcome variable (EVIDIF). In the results section, we present the descriptive statistics of EVI in different forms and periods.

We use an Ordinary Least Squares (OLS) to estimate the effect of certifications on vegetation health and density change by estimating the following model:

$$Y_i = \beta_0 + \beta_1 VSS + \beta_2 F_i + \beta_3 X_i + \beta_4 P_i + \varepsilon_i \quad (10).$$

The outcome variable Y represents the average vegetation health and density difference between 2020-2022 and 2001-2003 (EVIDIF) for household *i*. VSS is a binary variable that represents certifications. The control variable F includes variables associated with coffee production, namely the amount of coffee produced, the size of the coffee plot, the elevation of the coffee plot, the use of shade trees and organic farming methods, and the application of fertilizers, insecticides, and fungicides. The vector X includes household-related variables, such as income from activities not related to coffee production, household size, the literacy level of the household head, the age of the household head, coffee price per kilogram, and the share of land owned and allocated to agriculture. The vector P is a dummy variable equal to 1 for the Southern Province and equal to 0 for the Western Province.

We acknowledge that the binary variable VSS is potentially endogenous. However, due to the zoning policy that obliges farmers to sell their coffee production only to their designated CWS and prohibits sales or purchases outside these zones and designations, we consider that selection bias at a farm level is very unlikely. Instead, selection bias can only be an issue at CWS level. For example, CWS located in greener areas are more likely to get certified. Therefore, we instrument the VSS variable at CWS level to reduce the bias that might arise from unobserved heterogeneity.

We use the ownership of the coffee washing station (CWS) allocated to the i-th household due to the zoning policy as an instrument. The variable equals 1 if a private organization or individual owns the CWS and 0 if a cooperative owns the CWS. We assume that CWSs are more likely to adopt certifications when they are owned by a cooperative (Wollni and Zeller 2007). We can attribute the higher probability of a CWS being certified to the cooperatives' superior organizational capabilities and greater financial resources than individual owners (Sellare et al. 2020), except for big exporters. Farmers that provide coffee to a CWS owned by a cooperative are not necessarily members of that cooperative.

Finally, we test for weak identification and reject the null that our instrument and our treatment are not correlated. The F-statistic is 133.06, and the t-statistic is 11.536, exceeding the Stock-Yogo critical values **(Appendix C)**. Moreover, similarly to Di Falco et al. (2011), we perform a falsification test to determine the validity of our instrument and to ensure that it is uncorrelated with our outcome variable **(Appendix D)**. Our falsification test suggests that our instrument strongly correlates with our treatment variable but does not correlate with our outcome variable when the treatment is not a mediator.

3.2.3 Causal Mediation Analysis: certifications, agricultural productivity, and vegetation density

In addition to exploring the effect of VSS on farmers' agricultural productivity and deforestation, we further examine the mechanism behind the treatment effect. To do so, we follow the method proposed in Imai et al. (2011), which aims to decompose the total causal effect of certifications on vegetation density into the sum of the indirect and direct mediation effects. Imai et al. (2011) define a causal mechanism as the process of a treatment variable T affecting an outcome *Y* through an intermediate variable or mediator *M*. The causal mediation analysis aims to decompose the total causal effect of *T* on *Y* into indirect and direct effects, where the latter represents the hypothesized causal mechanisms and the former all other possible mechanisms (Imai et al. 2011). Then, following Imai et al. (2011), the causal mediation effect can be defined as

$$\delta_i(t) = Y_i\big(t, M_i(1)\big) - Y_i\big(t, M_i(0)\big) \qquad (11).$$

Where $\delta_i(t)$ represents the change in Y if there is a change in the mediator from control $M_i(0)$ to the treatment condition $M_i(1)$ holding the treatment status at *t*. We need to estimate $M_i(0)$ for the observations in the treatment group, as it cannot be directly observed.

The direct effect $\varphi_i(t)$ is the remaining effect after $\delta_i(t)$ has been estimated and can be written as:

$$\varphi_i(t) = Y_i\big(1, M_i(t)\big) - Y_i\big(0, M_i(t)\big); \quad t = 0,1. \qquad (12)$$

Where $\varphi_i(t)$ represents the causal effect of the treatment on the outcome if there is a change in the treatment status from $t_i = 0$ to $t_i = 1$, and holding the value of the mediators constant. When considering all individuals *i*, the average causal mediation effect (ACME) is $\delta_i(t)$ and the average direct effect (ADE) is $\varphi_i(t)$. The average treatment effect (ATE) is $\delta_i(t) + \varphi_i(t)$.

However, mediation analysis depends on the Sequential Ignorability Assumption (SIA) (Imai et al., 2011), to calculate ADE and ACME (Imai et al. 2011). First, the treatment assignment must be independent of outcomes and mediator variables. Second, the mediator status must be ignorable once we have controlled for actual treatment status and mediator variables. Finally, we assume a linear relationship between the treatment, the mediators, and the outcome. We anticipate these assumptions to be valid because certifications in Rwanda were exogenous to the farmers and their production systems. However, in the next Section, we investigate whether certified CWS were located in greener areas prior to the start of certification activity in our sampling area.

Our mediation analysis is based on our conceptual framework described in Section 2.1. Our treatment variable is the certification status of farmer *i* (VSS). The outcome variable is the difference between the average enhanced vegetation index within a radius of 500 meters from the coffee plot in 2020-2022 and 2001-2003 (EVIDIF). The mediators based on our conceptual framework are technical efficiency (TE), technological gap ratio (TGR), and shade trees at the coffee plot level (SHADETREES). We decompose the total treatment effect obtained from our balanced sample into the indirect effect, namely, the effect of VSS on the change of vegetation health and density that occurs through agricultural TE, TGR, and shade trees. The direct effect represents everything we do not mediate for, potentially the regulatory capacity of VSS to foster a change in EVIDIF scores for farmer *i*. We use lagged vegetation health as the outcome variable and bootstrap our estimates 1000 times to minimize the bias from unobserved factors.

4 Results and discussion

4.1 Descriptive statistics

Table 1 shows the descriptive statistics for our socioeconomic variables and the t-test results comparing certified and non-certified farmers. Certified farmers produce, on average, more coffee than non-certified farmers with similar amounts of land, labor, fertilizer, insecticide, fungicide, more shade trees, and fewer coffee trees per hectare. These data imply that certified farmers have higher coffee tree productivity. Additionally, a larger proportion of certified farmers implement organic practices and plant shade trees, whereas a smaller percentage use inorganic fertilizers and insecticides compared to non-certified farmers.

Moreover, both farmer groups show similar average values for the gender of the household head, age of the household head, main occupation of the household head, household size, and income from other sources than coffee production. However, the group of certified farmers shows a higher proportion of farmers who know how to read and write, have an account at a financial institution, and belong to a cooperative. Additionally, on average, certified farmers own a bigger proportion of the land they manage, have a greater proportion of their land under agriculture, and have more farming experience than non-certified farmers.

Table 1: Descriptive statistics of socioeconomic variables

Variable	Definition	Pooled		Certified		Non-certified		
		Mean	SD	Mean	SD	Mean	SD	T-test
Coffee production-related variables								
PROD	Total coffee production in kilograms	688.90	765.11	724.29	765.19	633.15	762.82	-1.69*
LAND	Land size in hectares	0.14	0.21	0.14	0.21	0.14	0.22	0.03
LABOUR	Total labor expressed in total days	186.86	265.79	191.36	248.73	179.78	290.88	-0.59
DENSITY	Number of trees per hectare	2992	1591	2913	1532	3117	1674	1.77*
AGECOFFEE	Age of the coffee plantation	26.04	15.27	25.75	14.66	26.48	16.20	0.66
FERTILIZER	Total fertilizer expenses in USD	18.13	36.26	18.14	38.82	18.10	31.89	-0.02
INSECTICIDE	Total insecticide expenses in USD	0.26	1.10	0.21	0.71	0.34	1.53	1.36
FUNGICIDE	Total fungicide expenses in USD	0.46	1.20	0.45	1.12	0.48	1.33	0.36
SHADETREES	Number of shade trees	10.35	9.66	12.23	9.71	7.39	8.80	-7.45***
$ORGANIC_d$	1 if farmers applied organic practices, 0 otherwise	0.71	0.45	0.75	0.43	0.64	0.48	-3.32***
$FERTILIZER_d$	1 if farmers applied inorganic fertilizer, 0 otherwise	0.89	0.32	0.86	0.34	0.93	0.26	3.07***
$INSECTICIDE_d$	1 if farmers applied insecticide, 0 otherwise	0.68	0.46	0.61	0.49	0.77	0.42	4.90***
$FUNGICIDE_d$	1 if farmers applied fungicide, 0 otherwise	0.30	0.46	0.29	0.45	0.32	0.47	0.82
$SHADETREES_d$	1 if farmers have shade trees, 0 otherwise	0.89	0.46	0.98	0.39	0.74	0.50	-7.25***
Farm and household characteristics								
AGE	Age of the household head in years	55.34	12.96	55.75	12.41	54.69	13.78	-1.12
GENDER	1 if the household head is male, 0 otherwise	0.75	0.43	0.75	0.43	0.76	0.42	0.30
LITERACY	1 if the household reads and write, 0 otherwise	0.80	0.40	0.82	0.38	0.77	0.42	-1.79*
OCCUPATION	1 if the main occupation of the	0.93	0.25	0.94	0.23	0.91	0.28	-1.58

	household head is farmer, 0 otherwise							
EXPERIENCE	Years of farming experience of the household head	33.63	15.74	34.43	15.07	32.36	16.70	-1.82*
HHSIZE	Number of household members	4.98	2.17	4.98	2.18	4.97	2.15	-0.05
INCOME	Total income from all other sources than coffee production	885.50	1160.76	925.50	1187.05	822.52	1117.00	-1.27
OWNLAND	Proportion of the managed land owned by the farmers: 1 if 0%; 2 if > 1 and < 50%; 3 if = 50%; 4 if > 50% and < 100%; 5 if = 100%	4.64	0.75	4.68	0.67	4.57	0.85	-1.80*
AGLAND	Proportion of the managed land under agriculture: 1 if 0%; 2 if > 1 and < 50%; 3 if = 50%; 4 if > 50% and < 100%; 5 if = 100%	2.69	0.62	2.72	0.60	2.65	0.66	-1.64
ACCOUNT	1 if the household head owns an account at a financial institution, 0 otherwise	0.83	0.38	0.87	0.34	0.76	0.42	-3.71***
COOPERATIVE	1 if the household head is a cooperative member, 0 otherwise	0.53	0.50	0.64	0.48	0.37	0.48	-7.94***
AGMARKET	Distance to the closets agricultural market (km)	4.38	3.77	4.64	3.71	3.96	3.82	-2.52**
PROVINCE	1 if farmers is from Southern Province	0.23	0.42	0.25	0.43	0.20	0.40	-1.75*
ALTITUDE	Plot height in relation to sea level	1684	239.31	1673.88	233.94	1698.85	247.13	1.45
Observations		842		515		327		

***Note:* ***, **, *** means significant at the 1%, 5%, and 10% level, respectively, across the group of certified and non-certified farmers.

Table 2 shows the descriptive statistics for our environmental variable at the plot and landscape levels and the t-test results comparing certified and non-certified farmers. Non-certified farmers display a higher vegetation health and density value than certified farmers for 2003-2001 at plot and landscape levels. These values imply that a higher level of vegetation density did not influence the adoption of certifications. The pooled sample shows that the sampled area has undergone vegetation degradation (EVIDIFPLOT and EVIDIFLS). However, the rate at which this happened has been slower for certified farmers than for non-certified farmers, leading to a higher EVI average in 2020-2022 for certified farmers than for non-certified farmers. In the following sections, we will discuss the role of VSS in slowing down the degradation of vegetation density and health.

Table 2: Descriptive statistics of EVI

Variable	Definition	Pooled		Certified		Non-certified		
		Mean	SD	Mean	SD	Mean	SD	T-Test
$EVIPLOT_{2001-2003}$	Average EVI in a radius of 500m in 2001-2003	0.42	0.07	0.41	0.08	0.43	0.07	2.90***
$EVIPLOT_{2020-2022}$	Average EVI in a radius of 500m in 2020-2022	0.39	0.08	0.40	0.08	0.39	0.08	-2.8***
EVIDIFPLOT	Difference between $EVIPLOT_{2020-2022}$ and $EVIPLOT_{2001-2003}$	-0.02	0.08	-0.01	0.08	-0.04	0.07	-5.56 ***
$EVILS_{2001-2003}$	Average landscape EVI value using convex hull by CWS in 2001-2003	0.42	0.06	0.41	0.07	0.43	0.06	4.72***
$EVILS_{2020-2022}$	Average landscape EVI value using convex hull by CWS in 2020-2022	0.39	0.06	0.40	0.06	0.39	0.06	-2.52**
EVIDIFLS	Difference between $EVILS_{2020-2022}$ and $EVILS_{2001-2003}$	-0.02	0.05	-0.01	0.05	-0.04	0.05	-8.40***
Observations		**842**		**515**		**327**		

***Note:* ***, **, *** means significant at the 1%, 5%, and 10% level, respectively, across the group of certified and non-certified farmers.

4.2 Stochastic frontier analysis

Our selection model (Greene 2010) fails to reject rho (ρ) for both certified and non-certified farmers. The non-significant rho suggests no bias from unobservable characteristics, and thus, the conventional stochastic frontier models yield consistent estimates and TE scores. A reasonable explanation for the absence of selection bias is the zoning policy assigning all farmers from a specific geographic location to a CWS, thereby ruling out self-selection into certification programs at the farmer level. **We provide the complete output for the selection model in Appendix A and Appendix B.**

Table 3 reports the estimates of the linear and dummy terms for the standard stochastic pooled and group models of our translog production functions. We limit ourselves to presenting only these results because translog production functions are not readily interpretable (Kim 1992), and our model fails to reject rho (ρ) for both certified and non-certified farmers. Therefore, following the parsimony principle, we use the conventional models to interpret our results further and calculate our meta-frontier. We normalize all variables by their sample mean values to directly interpret the first-order coefficient as partial production elasticities for the average producer (Coelli et al. 2003). **We provide the complete output of all five production functions in Appendix B: (1) Conventional pool SPF; (2) Conventional certified SPF; (3) Conventional non-certified SPF; (4) Sample-selection certified SPF; (5) Sample-selection non-certified SPF.**

Table 3: Stochastic frontier production functions

			Conventional SPF			
Variable	Pooled		Certified farmers		Non-certified farmers	
	Coeff.	SE.	Coeff.	SE.	Coeff.	SE.
Constant	6.21*	3.20	6.01	4.38	11.42**	4.70
Land	0.58***	0.03	0.56***	0.03	0.60***	0.05
Labor	0.10***	0.02	0.13***	0.03	0.06*	0.04
Tree density	0.39***	0.08	0.22**	0.10	0.61***	0.14
Age of plantation	0.03	0.03	0.01	0.04	0.05	0.06
Fertilizer	0.01	0.02	0.01	0.03	0.00	0.03
Insecticide	-0.08	0.12	-0.18	0.17	0.22	0.18
Fungicide	0.26	0.27	0.41	0.36	0.33	0.40
Shade Trees	0.03*	0.02	0.04**	0.02	0.03	0.03
Organic (dummy)	0.07	0.04	0.05	0.06	-0.00	0.07
Fertilizer (dummy)	-0.07	1.60	-0.49	2.09	0.15	2.45
Insecticide (dummy)	2.01	2.60	4.04	3.65	-3.88	3.76
Fungicide (dummy)	-3.08	2.98	-4.42	3.99	-4.49	4.45
Shade Trees (dummy)	-0.01	0.08	-0.01	0.09	0.07	0.14
Province	-0.03	0.06	-0.03	0.07	0.06	0.10
VSS	0.18***	0.04				
Lamda (λ)	1.69***	0.14	1.69***	0.17	2.19***	0.29
Sigma (σ)	0.78***	0.00	0.73***	0.00	0.82***	0.00
Log-Likelihood	-712.22		-399.49		-269.20	
N	**842**		**515**		**327**	

***Note:* ***, **, *** means significant at the 1%, 5%, and 10% level, respectively.

The pooled model indicates that certified farmers have significantly higher output levels, namely 18% more, compared with non-certified farmers. Furthermore, we observe differences in the frontier parameters for certified and non-certified farmers, and a likelihood ratio test (79.70[2], p-value = 0.00) rejects the null hypothesis of no difference between the pooled and the two individual group frontier models. Therefore, we estimate separate group frontiers to interpret the parameter estimates.

Examining the estimated production frontier parameters, as expected, land has a relatively large-first-order (linear) coefficient and is statistically significant in both the certified and non-certified frontiers. Labour

[2] $LR = 2 * \left((LnL_{CA} + LnL_{non-CA}) - Ln\ L_{pooled} \right)$

has a positive and significant linear coefficient for certified and non-certified farmers. While tree density is positive and significant for both group frontiers, it has a comparatively large first-order linear coefficient for non-certified farmers. Shade trees is positive and significant for certified farmers but non-significant for non-certified farmers. Interestingly, the fertilizer, insecticide, and fungicide estimates are insignificant, implying that there is potential to improve the use of these inputs.

Finally, the returns to scale (the sum of all partial production elasticities) for certified and non-certified farmers are 1.19 and 1.82, respectively, implying that certified and non-certified Rwandese coffee farmers have a technology characterized by increasing returns to scale (IRTS). In other words, if farmers increase all their inputs by 1%, they would increase their outputs at a proportion greater than 1%. Our results are consistent with those reported by Ngango and Kim (2018), who studied coffee production in the Northern Province of Rwanda. The fact that we find increasing returns to scale for both groups may be due to the small size of coffee farms in Rwanda, as shown in Table 1 and suggested by the positive and relatively large estimate for land. Coffee farmers can increase their production at over-proportional rates by expanding the size of their coffee plots and expanding labor. The sum of the partial elasticities for agrochemicals (fertilizer, insecticide, and fungicide) also reflects the limited access of farmers in Rwanda to agrochemicals, a concern frequently voiced by the local authorities (AgriLogic 2018). Finally, tree density is a larger determinant of productivity in non-certified farms than it is in certified ones. Our finding that certified farmers have higher production levels compared to non-certified farmers is in line with Jena et al. (2017), who found that FairTrade-certified farmers increase their coffee production compared to non-certified farmers because they invest more heavily in chemical fertilizers. Our results are also consistent with those of Beuchelt and Zeller (2011), who found that organic-certified farmers produce more than non-certified farmers due to increased organic fertilization and superior coffee management practices. Our findings closely resemble those of Beuchelt and Zeller (2011), as certified and non-certified farmers in our study employ similar levels of chemical fertilization (Table 1). Moreover, as indicated in Table 1, a larger proportion of certified farmers, compared to their non-certified counterparts, complement their chemical fertilization with organic fertilization.

4.2.1 Coffee farmers' technical efficiency and productivity

The statistical significance of lambda (λ) implies that the inefficiency of farmers is relatively important in explaining the deviation of the observed output from their frontier output. Moreover, we identified a potential production technology gap between certified and non-certified farmers in the previous Section because SPF parameters differ across groups. Then, following Huang et al. (2014), we estimate a stochastic meta-frontier production frontier among certified and non-certified coffee farmers in Rwanda. We use the meta-frontier estimates to calculate the meta-frontier technical efficiency (MTE) and the technology gap ratio (TGR) to compare certified and non-certified farmers.

Table 4 presents the sample statistics of several efficiency scores for the two groups of farmers. The group-specific TE scores for certified and non-certified farmers are 0.63 and 0.59, respectively. This suggests that, within their respective groups, certified farmers are, on average, more technically efficient than non-certified farmers. This is also reflected in the technical efficiency estimates derived from the meta-frontier, as indicated by significantly higher MTE estimates for certified farmers compared to non-certified farmers. Our results further suggest that farmers' technical inefficiency (TE) and farmers' failure to adopt the best available practices and technology (TGR) are important factors in explaining the low meta-frontier technical efficiency (MTE). Finally, the technology gap ratio (TGR) scores derived from the meta-frontier suggest that certified farmers are slightly better at adopting the best available agricultural technology and practices than non-certified farmers. The average TGR score for certified farmers is 0.64, and for non-certified farmers is 0.61.

Table 4: MTE, TE, and TGR scores

	Pooled sample		Certified farmers		Non-certified farmers		
Variable	Mean	SD	Mean	SD	Mean	SD	T-Test
TE	0.61	0.15	0.63	0.15	0.59	0.17	-3.44***
TGR	0.62	0.16	0.64	0.16	0.61	0.17	-1.92*
MTE	0.40	0.18	0.42	0.18	0.39	0.19	-2.51**

***Note:* ***, **, *** means significant at the 1%, 5%, and 10% level, respectively, across the group of certified and non-certified farmers.

The results presented in Table 4 suggest that certification is associated with increases in average technical efficiency by 4% and TGR by 3%. Increases in technical efficiency are likely driven by the fact that VSS encourage farmers to attend training on sustainable coffee production and optimal input use, thus contributing to increasing farmers' managerial ability. Improvements in the technological gap ratio (TGR) may be linked to VSS promoting new technologies and practices. For example, certifications aim to reduce reliance on external inputs by promoting an integrated pest management approach and endorsing organic farming practices, minimizing the use of external organic or inorganic fertilizers (Rainforest Alliance 2023).

Table 5 presents the mean comparison of several observed and frontier production measures with respect to farmers' own group frontiers. *Observed* output refers to the actual coffee production, whereas *frontier* output refers to the average expected coffee production if all farmers within the group increase their efficiency to 100%. These results indicate that certified farmers obtain observed output levels that are 16% higher compared to non-certified farmers. Moreover, the results in Tables 4 and 5 suggest that certified and non-certified farmers can increase their output to 1086 and 1000 kilograms on average, respectively. The average frontier output is not significantly different for certified and non-certified farmers, implying that there would be no differential output across groups if all farmers produced at 100% efficiency. In other words, certified farmers increase their output mostly due to their managerial abilities rather than a shift in the production frontier.

Table 5: Average observed and frontier yield for certified and non-certified farmers

	Certified farmers	Non-certified farmers	Test of means
Average observed output (kg)	724	624	-1.69*
Average frontier output (kg)	1086	1000	-0.91
Observed yield per hectare (kg/ha)	7,484	7,108	-0.88
Frontier yield per hectare (kg/ha)	11,249	11,367	0.21
Observed tree productivity (kg/tree)	2.70	2.32	-2.91***
Frontier tree productivity (kg/tree)	4.06	3.71	-2.32**

***Note:* ***, **, *** means significant at the 1%, 5%, and 10% level, respectively.

Table 5 further shows no significant difference in the average observed and frontier yields per hectare across groups. These results suggest variation in input productivity across groups, as also observed in Tables 1 and 3, suggesting that certified and non-certified farmers use different approaches to boost their production. Certified farmers must keep a minimum proportion of shade trees and give up some coffee trees. Thus, they rely on increasing productivity per tree by applying good agricultural practices to keep productivity per hectare high. In contrast, non-certified farmers rely mainly on intensifying coffee tree density (more coffee trees per unit of land). Our results suggest that reducing coffee trees in favor of planting more shade trees does not need to come at the cost of lower coffee output per hectare.

4.3 Changes in vegetation density and health

In this Section, we present the results of the effects of VSS on changes in vegetation health and density in a radius of 500 m around the coffee plot. A Wu-Hausman test **(Appendix C)** reveals that the certification status of farmers is not endogenous to landscape-level vegetation change. Therefore, we will refer to the ordinary least square (OLS) estimation for subsequent discussion, given that in the absence of endogeneity bias, OLS is considered more efficient than 2-SLS (IV) (Wooldridge 2011). We present the full OLS and IV model output and robustness checks using NDVI instead of EVI as an outcome measure in **Appendix C.**

Table 6 presents our OLS and IV results. While certified and non-certified farmers have experienced a reduction in the vegetation health and density within a radius of 500 m surrounding their coffee plots (Table 2), being certified has slowed down the degradation rate by 3%. In the following Section, we further discuss the potential mechanisms through which certification may help protect vegetation health and density.

Table 6: Effects of sustainability standards (VSS) on vegetation health and density (EVIDIF)

	EVIDIF (OLS)	EVIDIF (IV)
CONSTANT	-0.10*** (0.04)	-0.10** (0.04)
VSS	0.03*** (0.01)	0.04** (0.01)
CONTROLS	YES	YES

***Note:* ***, **, *** means significant at the 1%, 5%, and 10% level, respectively.

4.4 Potential mechanisms of the effect of VSS on vegetation density and health

Based on the conceptual framework outlined in Section 2, we apply mediation analysis to investigate how VSS affect changes in vegetation density and health. We hypothesize two potential pathways through which VSS could affect EVIDIF. The first is by promoting the planting of shade trees and increasing the proportion of shade on the coffee plot. The second is improving agricultural productivity (production per tree), which can have a land-sparing effect. Another pathway that we cannot directly control but is captured in the direct effect of VSS refers to the regulatory capacity of VSS to protect forests and trees, which prohibits coffee production systems from expanding into natural forests or ecosystems and promotes the restoration of areas with conservation value outside the coffee plot.

Figure 2 shows the results of our mediation analysis, which are consistent with our results in Table 6. They suggest that VSS affect vegetation health and density positively (EVIDIF), consistent with other findings (Rueda et al. 2015; Haggar et al. 2015; Hardt et al. 2015; Haggar et al. 2017; Takahashi and Todo 2017). Similar to what was discussed in the previous Section, our mediation analysis shows that certifications increase coffee tree productivity by improving farmers' technical efficiency. However, coffee tree productivity does not affect vegetation health and density. This is perhaps related to what we discussed in the previous Section, that the average scale of coffee production in Rwanda is too small, and land is the main limiting input in Rwandese agriculture (AgriLogic 2018). In other words, an increasing return to scale represents an incentive to expand coffee production.

On the other hand, Figure 2 also shows that certifications lead to a higher number of shade trees at a coffee plot level by promoting agriculture-sustainable practices, which also contributes positively to a higher vegetation density at a landscape level. This finding is consistent with Rueda et al. (2015), who suggest that certified plots significantly increase their tree cover compared to non-certified farms. Perhaps this is because voluntary standards require a minimum proportion of shade trees on a coffee plot to issue a certification, and they do not allow the removal of native trees from the coffee plots (Café Practices 2016; Rainforest Alliance 2023).

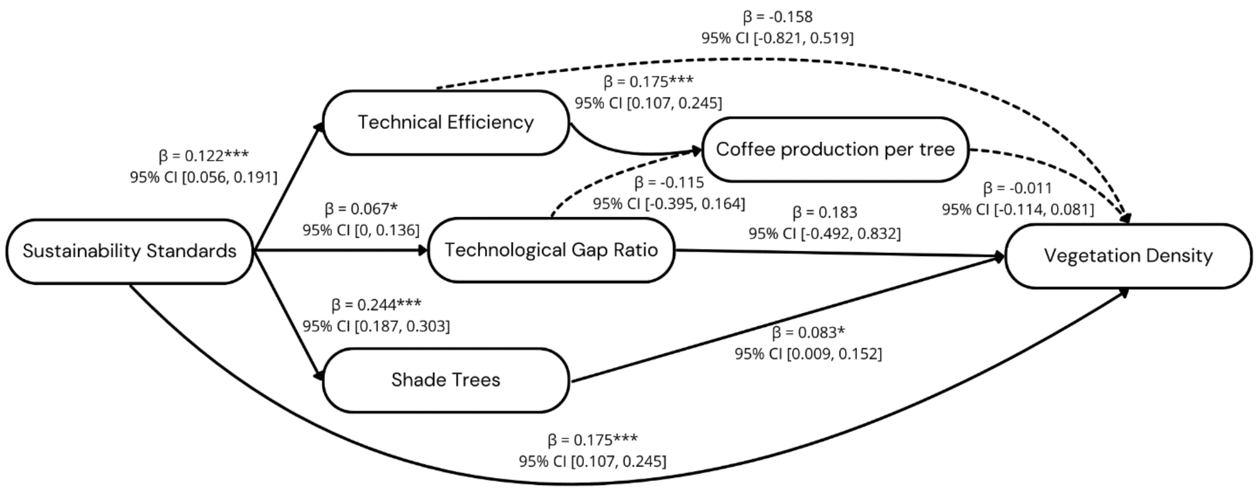

Figure 2: Mechanisms for which VSS affect Vegetation Health and Density

Finally, the estimate for the direct effect (everything we have not controlled for) shows a positive and the largest estimate. This effect is most likely the VSS's regulatory mechanism to protect vegetation health and density. Hardt et al. (2015) suggest that VSS's regulatory capacity plays the most important role in lowering deforestation rates for vegetation cover and enhancing habitat availability and connectivity. For example, the Rainforest Alliance (2023) and Café Practices (2016) state that production systems cannot expand into natural forests or other natural ecosystems. Moreover, the Rainforest Alliance (2023) promotes the conservation and restoration of areas with conservation value outside the certified farm.

5 Conclusion

This study examines the impact of VSS on Rwandese coffee farmers' technical efficiency and productivity while exploring the trade-offs and mechanisms between certification, productivity, and forest protection. We first use a stochastic frontier analysis with correction for sample selection to analyze the effect of VSS on technical efficiency and productivity. We then use regression analysis to estimate the effect of VSS on the change in vegetation health and density. Finally, we use a mediation analysis to uncover the potential mechanisms that link the relationship between VSS and EVIDIF. Our study first concludes that VSS serve a dual purpose in Rwandan coffee-producing systems, increasing coffee production while protecting vegetation density and health in the areas surrounding the coffee plot. Second, VSS increase TE and the actual observed coffee output. Third, certified farmers exhibit similar input use but higher input productivity. Fourth, adopting VSS leads to higher coffee tree productivity but not higher land productivity. Fifth, VSS have a positive effect on vegetation health and density. Lastly, the regulatory capacity of VSS is their strongest mechanism to protect vegetation health and density.

This study provides insights for evidence-based policymaking in tropical crops and forest preservation that can also be relevant to other tropical areas and commodities. Our research suggests that VSS can be a valuable component of a more comprehensive rural development initiative within the Rwandese coffee industry because they can help to increase coffee output due to improvements in technical efficiency. Furthermore, certified farmers reported similar input use levels and higher coffee production levels than non-certified farmers. This suggests that VSS can support farmers in increasing their production by promoting GAPs without increasing input use. This last implication aligns with the Rwandese government's coffee plan to increase the quantity and quality of coffee production within a context where agricultural inputs are limited.

Coffee farmers in Rwanda experience low levels of technical efficiency and limited access to the most available practices and technology, showing a considerable untapped potential to increase coffee productivity in the Rwandese coffee belt. In this context, voluntary sustainability standards can help reduce this gap and complement agricultural development programs such as the fertilizer fund co-run by CEPAR and NAEB that provides coffee farmers with inputs.

Moreover, our study suggests that VSS may help protect forests, largely due to their capacity to serve as private regulatory instruments. However, much like the perspective of Garrett et al. (2021), our stance is that VSS should not be considered a substitute for centralized public governance concerning common pool resources. Therefore, VSS can complement and strengthen national programs, such as Rwanda's National Forest Policy, but certainly not replace them.

Future research should adopt a long-term perspective using panel data to account better for unobserved heterogeneity and measure the long-term effects of VSS. Our study uses VSS as an aggregated variable without distinguishing between different schemes, implying that all certifications serve a dual purpose. Further research should focus on different certification schemes in order to differentiate their capacity to protect vegetation density and health. Although our paper focuses on VSS implementation at a farmers' level, recent research suggests that the effect of certification at a farmer's level may also be affected by its implementation and operationalization by the certificate holders (CWS). Therefore, studying the operationalization by CWS in Rwanda would provide more insights into the capacity of VSS to serve the dual purpose. Furthermore, our study focuses only on each farmer's most productive coffee plot, meaning that we may be underestimating the lack of resources that coffee farmers reported in this study. Extending analyses like this to the whole farm could provide valuable insights into household welfare and its interaction with natural resources when VSS are adopted. Finally, future research should look closer at the vegetation types to gain a deeper understanding of the relationship between agricultural productivity and deforestation when VSS are implemented.

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A. Probit sample-selection model: Adoption of certifications

Variable	Coefficient (SE)	Marginal Effect (SE)
CONSTANT	-1.98*** (0.51)	
GENDER	-0.12 (0.12)	-0.04 (0.04)
AGE	0.00 (0.01)	0.00 (0.00)
LITERACY	0.26** (0.12)	0.09418** (0.04)
OCCUPATION	0.20 (0.18)	0.07 (0.07)
EXPERIENCE	0.00 (0.00)	0.00 (0.00)
HH SIZE	0.01 (0.02)	0.00 (0.01)
INCOME	0.00 (0.00)	0.00 (0.00)
OWNLAND	0.11* (0.06)	0.04* (0.02)
AGRILAND	0.14** (0.07)	0.05** (0.02)
ACCOUNT	0.34*** (0.12)	0.12*** (0.04)
COOPERATIVE	0.66*** (0.09)	0.24*** (0.03)
AGMARKET	0.03** (0.01)	0.01** (0.00)
Log-likelihood function	-516.75409	
Chi-squared test statistic	91.41951***	
Number of observations	842	

***Note:* ***, **, *** means significant at the 1%, 5%, and 10% level, respectively.

B. Stochastic-frontier models

		CONVENTIONAL SPF		SAMPLE-SELECTION SPF	
	POOLED	CERTIFIED	NON-CERTIFIED	CERTIFIED	NON-CERTIFIED
CONSTANT	6.21* (3.20)	6.01 (4.39)	11.42** (4.70)	5.36 (6.15)	10.16 (6.95)
LAND	0.58*** (0.03)	0.56*** (0.03)	0.60*** (0.05)	0.56*** (0.05)	0.61*** (0.06)
LABOUR	0.10*** (0.02)	0.12*** (0.03)	0.06* (0.04)	0.13*** (0.03)	0.06 (0.05)
DENSITY	0.39*** (0.08)	0.22** (0.10)	0.61*** (0.14)	0.25** (0.12)	0.61*** (0.18)
AGECOFFEE	0.03 (0.03)	0.01 (0.04)	0.05 (0.06)	0.02 (0.05)	0.05 (0.07)
FERTILIZER	0.001 (0.02)	0.01 (0.03)	0.00 (0.03)	0.00 (0.06)	-0.01 (0.03)
INSECTICIDE	-0.08 (0.12)	-0.18 (0.17)	0.22 (0.18)	-0.21 (0.21)	0.19 (0.28)
FUNGICIDE	0.26 (0.27)	0.41 (0.36)	0.33 (0.40)	0.45 (0.38)	0.29 (0.50)
SHADETREES	0.03* (0.02)	0.04** (0.02)	0.03 (0.03)	0.04* (0.02)	0.02 (0.04)
$LAND^2$	0.12*** (0.04)	0.16*** (0.05)	0.05 (0.07)	0.16** (0.06)	0.03 (0.09)
$LABOUR^2$	0.00 (0.03)	-0.03 (0.03)	0.02 (0.05)	-0.03 (0.04)	0.01 (0.06)
$DENSITY^2$	0.23 (0.19)	0.46* (0.24)	-0.58 (0.36)	0.41 (0.31)	-0.57 (0.55)
$AGECOFFEE^2$	0.01 (0.06)	-0.07 (0.08)	0.09 (0.09)	-0.07 (0.09)	0.09 (0.11)
$FERTILIZER^2$	-0.00 (0.01)	-0.00 (0.01)	-0.00 (0.02)	-0.00 (0.02)	0.00 (0.02)
$INSECTICIDE^2$	0.02 (0.02)	0.03 (0.03)	-0.03 (0.03)	0.04 (0.04)	-0.02 (0.05)
$FUNGICIDE^2$	-0.02 (0.03)	-0.04 (0.03)	-0.02 (0.04)	-0.05 (0.04)	-0.02 (0.05)
$SHADETREES^2$	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)
LAND*LABOUR	-0.04* (0.02)	-0.04 (0.03)	0.00 (0.04)	-0.04 (0.03)	0.01 (0.06)
LAND*DENSITY	0.09 (0.07)	0.11 (0.09)	-0.12 (0.11)	0.10 (0.13)	-0.13 (0.17)
LAND*AGECOFFEE	0.04 (0.03)	-0.03 (0.04)	0.13*** (0.05)	-0.03 (0.05)	0.11** (0.06)

LAND*FERTILIZER	-0.01 (0.00)	-0.01* (0.00)	0.02** (0.01)	-0.01 (0.01)	0.02 (0.02)
LAND*INSECTICIDE	0.00 (0.00)	0.00 (0.00)	0.00 (0.01)	0.01 (0.00)	0.01 (0.01)
LAND*FUNGICIDE	0.00 (0.00)	0.00 (0.00)	0.00 (0.01)	0.00 (0.00)	-0.00 (0.01)
LAND*SHADETREES	0.00 (0.01)	-0.00 (0.01)	0.02 (0.01)	-0.00 (0.02)	0.018 (0.01)
LABOUR*DENSITY	0.00 (0.06)	-0.03 (0.08)	0.16 (0.10)	-0.03 (0.10)	0.16 (0.16)
LABOUR*AGECOFFEE	0.01 (0.03)	0.01 (0.04)	0.00 (0.04)	0.01 (0.04)	0.018 (0.06)
LABOUR*FERTILIZER	0.01 (0.00)	0.01** (0.00)	-0.01 (0.01)	0.01* (0.00)	-0.02 (0.01)
LABOUR*INSECTICIDE	-0.00 (0.00)	-0.01 (0.00)	-0.00 (0.01)	-0.00 (0.00)	-0.00 (0.01)
LABOUR*FUNGICIDE	-0.00 (0.00)	-0.00 (0.00)	-0.01** (0.00)	-0.00 (0.00)	-0.01* (0.01)
LABOUR*SHADETREES	-0.01 (0.01)	-0.01 (0.01)	-0.02** (0.01)	-0.01 (0.01)	-0.02** (0.01)
DENSITY*AGECOFFEE	0.11 (0.08)	0.07 (0.11)	0.31** (0.14)	0.08 (0.14)	0.28 (0.21)
DENSITY*FERTILIZER	-0.03*** (0.01)	-0.04*** (0.01)	0.03 (0.02)	-0.04** (0.02)	0.03 (0.04)
DENSITY*INSECTICIDE	0.02** (0.01)	0.02 (0.01)	0.03 (0.02)	0.02 (0.02)	0.04 (0.02)
DENSITY*FUNGICIDE	-0.00 (0.01)	-0.01 (0.01)	-0.01 (0.01)	-0.00 (0.01)	-0.01 (0.02)
DENSITY*SHADETREES	-0.01 (0.02)	0.00 (0.03)	0.00 (0.02)	0.01 (0.04)	0.00 (0.03)
AGECOFFEE*FERTILIZER	-0.00 (0.00)	0.00 (0.00)	-0.01 (0.01)	-0.00 (0.00)	-0.01 (0.01)
AGECOFFEE*INSECTICIDE	0.00 (0.00)	0.00 (0.00)	-0.00 (0.01)	0.00 (0.01)	0.00 (0.01)
AGECOFFEE*FUNGICIDE	0.00 (0.00)	0.00 (0.00)	-0.00 (0.01)	0.00 (0.01)	-0.00 (0.01)
AGECOFFEE*SHADETREES	-0.01 (0.01)	0.00 (0.02)	-0.02 (0.01)	-0.00 (0.02)	-0.02 (0.01)
FERTILIZER*INSECTICIDE	0.00 (0.00)	0.00 (0.00)	-0.00* (0.00)	0.00 (0.00)	-0.00 (0.00)
FERTILIZER*FUNGICIDE	-0.00 (0.00)	-0.00*** (0.00)	0.00*** (0.00)	-0.00 (0.00)	0.00** (0.00)
FERTILIZER*SHADETREES	-0.00* (0.00)	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)
INSECTICIDE*FUNGICIDE	0.00 (0.00)	-0.00 (0.00)	0.00 (0.00)	-0.00 (0.00)	0.00 (0.00)

INSECTICIDE*SHADETREES	0.00 (0.00)	-0.00 (0.00)	0.00 (0.00)	-0.00 (0.00)	0.00 (0.00)
FUNGICIDE*SHADETREES	-0.00 (0.00)	0.00 (0.00)	-0.00 (0.00)	0.00 (0.00)	-0.00 (0.00)
$ORGANIC_{(D)}$	0.07 (0.04)	0.05 (0.06)	-0.00 (0.07)	0.05 (0.06)	-0.01 (0.09)
$FERTILIZER_{(D)}$	-0.08 (1.60)	-0.49 (2.09)	0.15 (2.46)	-0.19 (4.11)	0.77 (2.68)
$INSECTICIDE_{(D)}$	2.01 (2.60)	4.03 (3.65)	-3.88 (3.76)	4.65 (4.64)	-3.31 (5.97)
$FUNGICIDE_{(D)}$	-3.08 (2.98)	-4.42 (3.99)	-4.49 (4.45)	-4.88 (4.13)	-4.17 (5.56)
$SHADETREES_{(D)}$	-0.01 (0.08)	-0.01 (0.09)	0.07 (0.14)	0.01 (0.09)	0.11 (0.23)
PROVINCE	-0.03 (0.06)	-0.03 (0.07)	0.06 (0.10)	-0.04 (0.08)	0.06 (0.11)
$VSS_{(D)}$	0.18*** (0.04)				
Lambda (λ)	1.69*** (0.14)	1.69*** (0.17)	2.19*** (0.29)		
Sigma (σ)	0.78*** (0.00)	0.73*** (0.00)	0.82*** (0.00)		
Sigma-u (σ_u)				0.56*** (0.09)	0.69*** (0.10)
Sigma-v (σ_v)				0.42*** (0.05)	0.37*** (0.06)
Rho-w,v ($\rho_{(w,v)}$)				-0.28 (0.28)	-0.20 (0.41)
Log-Likelihood	-712.21933	-399.48560	-269.20038	-636.99857	-551.70749
N	842	515	327	515	327

Note: ***, **, * means significant at the 1%, 5%, and 10% level, respectively.

C. Comparison between OLS and IV Estimates using EVI and NDVI as outcomes

	EVI		NDVI	
	OLS (S.E.)	IV (S.E.)	OLS (S.E.)	EVI (S.E.)
CONSTANT	-0.10** (0.04)	-0.10** (0.04)	-0.15** (0.05)	-0.16** (0.05)
VSS	**0.03*** (0.01)**	**0.04** (0.01)**	**0.04*** (0.01)**	**0.03 (0.02)**
ALTITUDE	0.00* (0.00)	0.00** (0.00)	0.00 (0.00)	0.00 (0.00)
INCOME	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)
LAND	-0.01 (0.02)	-0.01 (0.02)	-0.01 (0.02)	-0.02 (0.02)
PROD	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
HHSIZE	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)
LITERACY	-0.01 (0.01)	-0.01 (0.01)	-0.01 (0.00)	-0.01 (0.01)
AGE	-0.00 (0.00)	-0.00 (0.00)	0.01 (0.00)	0.00 (0.00)
PRICE	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)	-0.00 (0.00)
OWNLAND	0.01 (0.00)*	0.01* (0.00)	0.00 (0.00)	0.00 (0.00)
AGRILAND	-0.00 (0.00)	-0.00 (0.00)	-0.01 (0.01)	-0.01 (0.01)
$ORGANIC_D$	0.00 (0.01)	-0.00 (0.01)	-0.00 (0.01)	-0.00 (0.01)
$FERTILIZER_D$	0.01 (0.01)	0.01 (0.01)	0.00 (0.01)	0.00 (0.01)
$INSECTICIDE_D$	0.02** (0.01)	0.02** (0.01)	0.01 (0.01)	0.00 (0.01)
$FUNGICIDE_D$	0.00 (0.01)	0.00 (0.01)	0.00 (0.00)	0.00 (0.00)
$SHADETREES_D$	0.02** (0.01)	0.01* (0.01)	0.02** (0.01)	0.03** (0.01)
PROVINCE	0.03*** (0.08)	0.028*** (0.01)	0.1*** (0.01)	0.1*** (0.01)

Diagnostic Tests (IV)

	df1	df2	statistic	p-value
EVI				
Weak IV	1	824	133.06	0.00***
Wu-Hausman	1	823	1.07	0.30
NDVI				
Weak IV	1	824	133.06	0.00***
Wu-Hausman	1	823	0.08	0.78

***Note:* ***, **, *** means significant at the 1%, 5%, and 10% level, respectively.

D. Falsification test (IV) with and without controls

	Model 1	Model 2
	Adoption of certifications	**EVI of non-certified farmers (EVI)**
IV (CWS OWNERSHIP)	-1.60*** (0.15)	-0.03 (0.02)
CONTROLS	**YES**	**YES**

Note: *****, **, *** means significant at the 1%, 5%, and 10% level, respectively.

	Model 1	Model 2
	Adoption of certifications	**EVI of non-certified farmers (EVI)**
IV (CWS OWNERSHIP)	-1.40*** (0.13)	-0.03 (0.02)
CONTROLS	**NO**	**NO**

Note: *****, **, *** means significant at the 1%, 5%, and 10% level, respectively.