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Tea Production Response to Seasonal Rainfall Variability: Evidence from Rwanda

Joseph Ndagijimana[1], Athanase Hafashimana[2]

[1]Department of Economics, College of Business and Economics, University of Rwanda, Rwanda
[2]The African Centre of Excellence in Data Science, University of Rwanda, Rwanda
Email: jndagijimana16@gmail.com, athanase.hafashimana@aims.ac.rw

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Abstract

Tea is a very important cash crop in Rwanda, as it provides crucial income and employment for farmers in poor rural areas. From 2017 to 2020, this study was intended to determine the impact of seasonal rainfall on tea output in Rwanda while still considering temperature, plot size (land), and fertiliser for tea plantations in three of Rwanda's western, southern, and northern provinces, western province with "Gisovu" and "Nyabihu", southern with "Kitabi", and northern with "Mulindi" tea company. The study tested the level of statistical significance of all considered variables in different formulation of panel data models to assess individual behaviour of independent variables that would affect tea production. According to this study, a positive change in rainfall of 1 mm will increase tea production by 0.215 percentage points of tons of fresh leaves. Rainfall is a statistically significant variable among all variables with a positive impact on tea output Q_{it} in Rwanda's Western, Southern, and Northern provinces. Rainfall availability favourably affects tea output and supports our claim. Therefore, there is a need for collaboration efforts towards developing sustainable adaptation and mitigation options against climate change, targeting tea farming and the government to ensure that tea policy reforms are targeted towards raising the competitiveness of Rwandan tea at local and global market.

Keywords

Tea Production, Climate Change, Production Technology, Seasonal Variability, Panel Data Models

1. Introduction

Climate change is considered as a major global challenge within agricultural sector and it has a particular effect on tea production [1]. Agriculture is highly dependent on climate change and a critical part of the economies in majority of developing countries, especially in Sub-Saharan Africa (SSA) [2]. SSA is considered highly vulnerable and perceived to have low resilience and adaptive capacity to climate change [3]. Increasingly irregular and erratic nature of weather conditions has a direct and, in most cases, adverse influence on quality and quantity of agricultural production, that creates additional burden on food security, threatens rural livelihoods and hampers efforts to reduce poverty.

Rwanda's economy is mostly reliant on agriculture [4]. As the backbone of the economy, this sector is critical for Rwanda's growth and poverty alleviation. It accounts for 33% of GDP [5], employs 80% of the labour force, and supplies raw materials to companies as well as a market for produced goods [6]. The average annual income in the country is $550 per capita, reflecting a rural poverty rate of 49%, which rises to 76% for families whose primary source of income is agriculture [7]. Agriculture, on the other hand, is one of the sectors most affected by ongoing climate change [8]. The strong trends in climate change that are already visible, the possibility of further changes, and the growing scope of possible climate consequences make it imperative to address agricultural adaptation more coherently [9]. Developing countries rely significantly on climate-dependent agriculture, and they are particularly vulnerable to climate change due to poverty and rapid population growth [10].

Recent studies highlighted that it is necessary to comprehend how agroecological management might enhance tea yields, quality, and farmers' livelihoods because little is known about its advantages over traditional tea management techniques [11]. Moreover, building climate-resilient tea systems requires taking care of agroecological, physiological, and molecular innovations to maintain sustainability in the tea production process [12].

Agriculture, in all of its forms and locations, remains extremely vulnerable to climate change. According to the Intergovernmental Panel on Climate Change [13], climate change is anticipated to significantly impact agricultural yields [14]. Because crops are sensitive to water shortages and heat stress, the agricultural sector will face major issues in the future decades [15], and some nations are already experiencing them. Furthermore, Rwanda's agricultural sector has limited diversification, with tea being the country's most important cash crop. Tea production contributes significantly to poverty reduction, job creation, foreign exchange profits, and is a major source of income for the majority of rural populations [16].

Tea is mostly grown in rainfed mono-cropping systems in certain agro-ecological zones, making it highly vulnerable to changes in agro-climatic factors that interfere with ideal growth and production circumstances [17]. Tea-producing areas in Rwanda are already experiencing climate change, which is "identified by changes in the mean and/or variability of its properties and that persists for an extended period, typically decades or longer" [18].

Higher temperatures, less and unpredictable rainfall, and more hail and frost events have occurred in the zones [19]. The variability of these agro-climatic conditions not only causes ecological stress and limits that affect the quantity and quality of tea yield, but it also has an impact on consumer demand, prices, rural livelihoods, and regional economies [20]. Tea output fluctuates despite efforts by government and non-government partners to provide economic incentives to growers in order to increase tea production. Climate change is likely to stymie these efforts by influencing farming decisions and negatively impacting realized output. As a result, rural livelihoods are jeopardized, and the country's development efforts are hampered.

Introduced in Rwanda in 1930, tea is currently cultivated on 26,274 hectares by 42,840 farmers in 12 districts, primarily in the country's Western, Southern and Northern, regions. In the first phase, the tea acreage is predicted to increase by more than 9000ha as a result of innovative volume-increasing tactics. In addition, tea farmer field schools were assisting farmers in implementing optimum agricultural practices and fertilizer use in an effort to increase productivity from the current 7.5 tons/ha to 9 tons/ha by 2020 [21]. The majority of tea produced in Rwanda is black, green, orthodox, white, organic, and spicy. The nation produces one of the highest-quality teas in the world; around 98.3 percent of it is exported in its raw form, with 70 percent sold at auction, 28.3 percent sold directly, and 1.7% marketed locally [22].

The tea industry plays a key role in Rwanda's socioeconomic development. It is a major source of foreign exchange earnings and contributes much to GDP. However, unpredictable trends in tea output over the past two decades have been related to climate-induced stress [23]. In the past, tea-growing regions in Rwanda were subject to harsh climate conditions, such as unpredictable rainfall. These events are anticipated to have negative socioeconomic repercussions on tea production. In other words, the impact of climate change on farming decisions is likely to hinder government and stakeholder initiatives [24]. Given the foregoing, this study seeks to ascertain the effects of climate change, operationalized as change in variability of rainfall, on tea production in Rwanda. To address the problem of limited production, technological advancements in water storage are necessary for sustainable business practices [25]. Although farming practices are sometimes performed by unskilled labour, particularly in developing countries, this crop needs a set of skills in pruning, skiffing, pest infestation, and drainage system management [26].

Recent studies highlighted that it is necessary to comprehend how agroecological management might enhance tea yields, quality, and farmers' livelihoods because little is known about its advantages over traditional tea management techniques [27]. Tea is one of the crops that is susceptible to extreme weather events, a study has been conducted on fluctuations in tea yield caused by extreme temperatures in China and found that both heat and cold extremes were associated with significantly reduced tea yields [28]. Moreover, its production is influenced by other climatic factors, but there was a positive relationship between mean air temperature and tea yields in Kenya.

Tea yield change can be associated with multiple decadal consequences of climate change, which can have significant repercussions on the livelihoods of farmers and labourers as well as on regional economies in general due to the fact that it is the second most consumed beverage worldwide [29]. In a changing climate, seasonal variation in rainfall is involved. Since some climate variables are interdependent, fluctuations in temperature may later cause variations in the rainfall received in a certain place [30].

The variables that are considered to affect the yield of tea such as plot size (land) and fertilizer can be controlled in the model [31]. Other climate variables such as temperature and rainfall may vary beyond the control of human interventions [32]. The explanatory variable of interest is to be specified according to the statistical significance [33]. The altitude difference between distinct four tea farms may also determine the difference in temperature as the temperature increases with decreasing altitude. The topographical nature of the country plays a great role in explaining temperature difference [34].

In Rwanda, there are two major rainfall seasons: the MAM season, extending from March to May, and the SON season, extending from September to November. Moreover, there is another season that is partly rainy and partly sunny, namely DJF which extends from December to February. Furthermore, there is a sunny season, which is JJA, that extends from June to August [35]. The seasonal rainfall may vary due to the orographic nature of the country. It is evident that rainfall increases linearly with elevation [36].

Several studies have analyzed the effects of climate change on crop production using experimental and non-experimental designs. [37], using simulation method, analysed the linear relationship between climate variables and tea production in Kenya. The results showed that in the presence of seasonality, a larger error term exists than in the absence of seasonality for most tea zones. Moreover, When the variance between the data-estimated tea production value and the constructed tea production using a linear regression equation is compared, it is typically the case that the seasonal data exhibits a bigger departure than the deseasoned data.

In [38], using time series data, it was observed that rainfall and temperature variation from their long-term means had significant effects on crop output in Uganda.

Therefore, this study adds knowledge to the limited but growing literature on climate change and tea production thereby availing information about the behavior of tea production variable and its relationship with rainfall, as the variable of interest in our analysis.

2. Data and Study Area

2.1. Data

Processed data in **Table 1** are available on the website of Rwanda Meteorology

Agency (Meteo Rwanda) that shall be shortly represented as **(Meteo Rw)**, a 5 km × 5 km daily gridded rainfall for Rwanda for 2017-2020 and temperature were considered during the analysis. Tea yields data, land and fertilizer were collected from National Agriculture Export Development Board **(NAEB)**. Since the region under study has a climatological history about total precipitation rate, the satellite observations from Climate Hazards Group InfraRed Precipitation with Station data **(CHIRPS)** have been used to see the relationship between geographical position of the tea plantation and associated amount of precipitation received. Furthermore, observed surface temperature from the Climate Research Unit **(CRU)**. Since the data from Rwanda Meteorology agency is of the high resolution, satellite observations have been regridded to the same grid sizes.

Table 1. Summary of the data used.

Source	Variables	Resolution
MeteoRw	Rainfall, Temperature	5 km × 5 km
NAEB	Land, Fertilizer, Yields	--
CHIRPS	Rainfall	0.25 × 0.25 (degree)
CRU	Surface temperature	0.5 × 0.5 (degree)

2.2. Study Area

Rwanda is a landlocked country in East Africa's central region. It is a small country in terms of geographical coverage, with a total area of approximately 26,338 km^2. It is situated in the small rectangular grid box of latitudes and longitudes. It is enclosed by longitudes of 28.5E and 31E and the latitudes of 3S and 1S. Uganda borders the country on the North, Tanzania on the east, Burundi on the South, and Democratic Republic of the Congo on the West. As you travel from East to West, the mountainous nature changes from low to high. In In addition, the topographical nature of the country aligns with the theoretical variation of temperature, where the temperature decreases with increasing altitude. The mountainous nature of the area also influences variations in the surface air temperature and creates fluctuations in rainfall received. The following maps in Figure 1 and Figure 2 describe the country.

3. Methods

3.1. Conceptual Framework and Specification of the Model

In this section, we construct the theoretical framework from Figure 3 based on the standard functional relationship. In fact, the theoretical framework for this study will be founded on the evaluation of the effect of climate change on tea production through the relationship between rainfall, as independent variable, and tea production, as dependent variable, while controlling temperature, land and fertilizer in the tea plantation regions of Western, Southern and Northern provinces of Rwanda in "Gisovu" and "Nyabihu", "Kitabi" and "Mulindi", respectively. The conceptual framework of this study is summarised below.

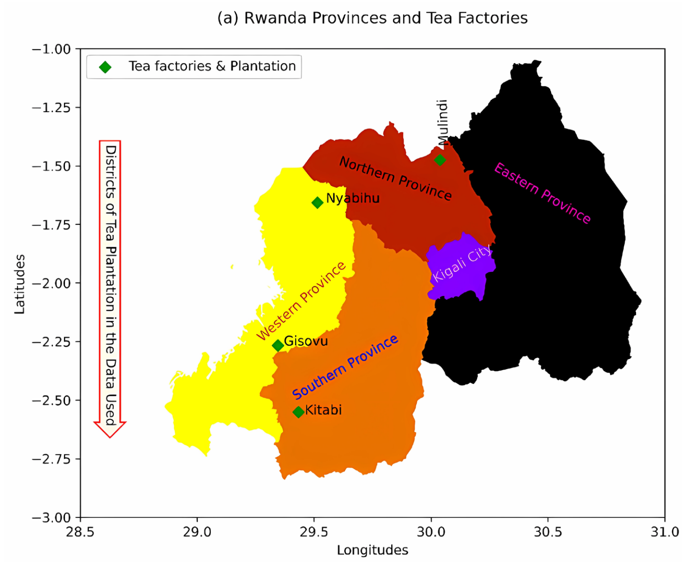

Figure 1. Provincial location of tea companies.

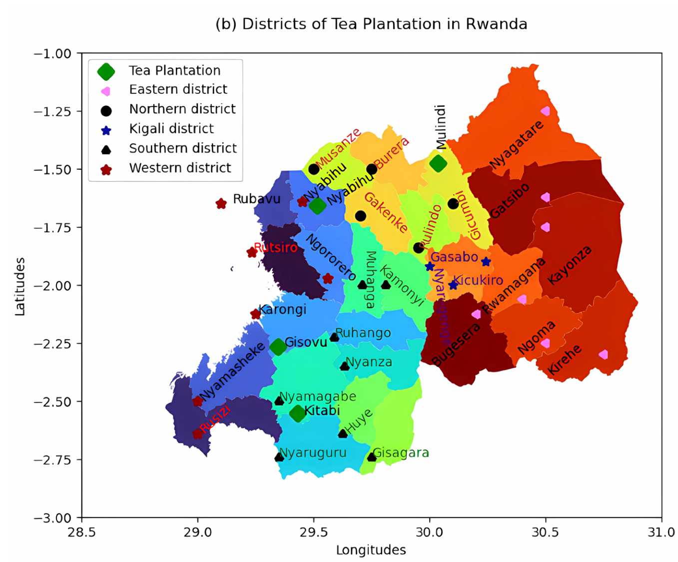

Figure 2. Districts location of tea companies

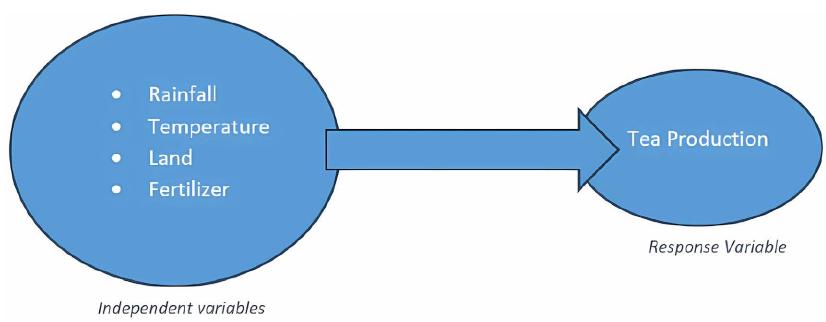

Figure 3. Variables considered in the model.

Majority of tea response studies and climate change are experimental studies and are unable to capture the dynamics of climate factors; like [39] who found that Sunshine hours and wind speed during summer had no direct effect on tea production in Bangladesh, while [40] using time series analysis with rainfall and temperature for tea output data in Bomet Central County of Kenya that had experienced increasing temperature and high rainfall distribution, found that effect of rainfall and temperature on tea production was unpredictable and non-significant in short period of time. To overcome the shortcomings in literature and to generate more precise estimates, this study estimated a panel data model that employed national long term data [41], sufficient enough to capture the effects of climate change on tea production, taking into account individual characteristics, by employing panel data analysis to test empirically the relationship between dependent and independent variables.

In the panel data analysis, this study was then possible and was conducted by making analysis of the tea production response to rainfall variability while controlling temperature, land and fertilizer for tea plantation in mountains of western, southern and northern regions of Rwanda, that are designated to be the most suitable regions of tea from 2017 to 2020. More data from satellite observation in total precipitation rate and surface air temperature were used to link the observed tea production and climatological characteristics of the regions to which the tea plantation belons. As each region has unique individual characteristics, we opted to employ balanced panel data analysis using Stata software to be able to empirically test the hypothesis in analyzing the effect of seasonal rainfall variability on tea production. Furthermore, Python has been used in many cases of generating research results.

As previously stated, four explanatory variables were chosen and examined in line with the regression analysis in order to evaluate the impact they have on tea production quantity (Q_{it}). Those explanatory variables are the following:

- Rainfall (Rf_{it}),
- Temperature ($Temp_{it}$),
- The plot size/Land (L_{it}) and
- Fertilizer (Fz_{it})

Therefore the model is given below:

$$Q_{it} = Q\left(Rf_{it}, Temp_{it}, L_{it}, Fz_{it}\right) \quad (1)$$

In fact, (1) can be detailed in the following way:

$$Q_{it} = \alpha_i + \beta_1 Rf_{it} + \beta_2 Temp_{it} + \beta_2 L_{it} + \beta_4 Fz_{it} + \varepsilon_{it} \quad (2)$$

The Equation (2) is the general formulation of model to use in evaluating how changing independent variables will cause the variation in the response variable Q_{it} . Since the tea production is depending on more than one variable, we are dealing with multiple regression problem. The way of developing critical understanding about how to estimate the parameters of a linear regression problem and significance of the predictors can be previewed https://online.stat.psu.edu/stat462/node/131/.

3.2. Panel Data Model

Panel Data Model is specific to analysing the behaviour of time series and cross section data. This is the case of our problem.

The p_value obtained for each predictor will tell us whether it is significant or not and help us to determine the best regression fitting the model in (2). General formulation of (2) defines a panel data and provides information on how to regulate non-observed components for time-invariant parameters (α_i) and time-variant parameters β_{it} t is described by the equation below:

$$Q_{it} = \alpha_i + \beta X_{it} + \varepsilon_{it} \tag{3}$$

where

i is individual observation, $i = 1,2,3,\cdots,N$ where N is the number of individuals.

t is an index for time dimension, $t = 1,2,3,\cdots,T$, where T is time period.

α represents an intercept of a model.

β represents a row vector of unknown parameters of estimates.

Q_{it} is an observation of the dependent variable for i and t. In our context, these are Tons of tea leaves of a specific tea factory.

X_{it} is a column vector of observation of the independent variables.

ε_{it} is the error term for i and t with zero mean and constant variance.

The Equation (3) that characterises the general equation of the panel data model has four necessary assumptions:

- The general equation of the panel data model is linear which means that each independent variable has its corresponding response.
- The independent variables (X_{it}) and time-invariant are linearly independent concerning error term. That is

$$\boldsymbol{E}\left[\varepsilon_{it} \mid X_{it}, \alpha_i\right] = 0 \tag{4}$$

- The variance of the error term is equal to sigma squared.

$$Var\left[\varepsilon_{it}\right] = \sigma^2 I \tag{5}$$

- The matrix of independent variables (X_{it}) is invertible which implies that Rank (X_{it}) = Full rank.

Among the three types of Panel data model, we have Pooled ordinary least square model, Fixed effects model, and Random effects model. Each of them has its own advantage and weakness. Luckily, the weakness of one type can be overcome by the other one.

3.2.1. Pooled Ordinary Least Square Model

Pooled OLS model explains a simple Ordinary Least Squares (OLS) model that is applied to panel data. It permits the linear relationship between response variable and independent variables, it does not account for correlation. It neglects the data containing two dimensions and assumes that the intercept (α) is constant for cross section and time series. The assumptions dictate the expectation of the error term to be zero and variance equal to σ^2. This relation implies that there is no correlation between observed variables (X_{it}) and unobserved (α_i). The Pooled OLS equation is given below:

$$Q_{it} = \alpha + \beta X_{it} + \varepsilon_{it} \tag{6}$$

Ordinary least square (OLS) estimator

The OLS estimates of unknown parameters α and β are consistent. Let us consider the Pooled OLS Equation (6) such that $\boldsymbol{E}\left[\varepsilon_{it}\right]=0$, $Var\left[\varepsilon_{it}\right]=\sigma^2 I$, and individual regressors are not really associated with time constant features of individuals (*i.e.* $corr\left(\alpha \mid X_{it}\right)=0$). The average of Equation (6) is given by the relation below:

$$\bar{Q}_{it} = \alpha + \beta \bar{X}_{it} + \bar{\varepsilon}_{it} \tag{7}$$

Taking (7) from (6) leads to:

$$Q_{it} - \bar{Q}_{it} = \beta\left(X_{it} - \bar{X}_{it}\right) + \left(\varepsilon_{it} - \bar{\varepsilon}_{it}\right) \tag{8}$$

Authorizing $Y = Q_{it} - \bar{Q}_{it}$; $X = X_{it} - \bar{X}_{it}$; $\varepsilon = \varepsilon_{it} - \bar{\varepsilon}_{it}$, transforms (8) into:

$$Y = \beta X + \varepsilon \Rightarrow \varepsilon = Y - \beta X \tag{9}$$

The Sum of Squared Errors (*SSE*) is therefore given by:

$$SSE = \sum_{j=1}^{N} \varepsilon_j^2 = \varepsilon^{\mathrm{T}} \varepsilon = \left(Y - \beta X\right)^{\mathrm{T}} \left(Y - \beta X\right)$$

Finally the sum of squared errors is as given by the following equation:

$$SSE = Y^{\mathrm{T}} Y - 2Y^{\mathrm{T}} X \beta + X^{\mathrm{T}} \beta^{\mathrm{T}} \beta X \tag{10}$$

The estimated vector of parameters $\hat{\beta}$ is the best linear unbiased estimator (BLUE) of β. To minimize the sum of squared errors (SSE), the partial differentiation of (10) is considered with respect to β. This yields the following:

$$\frac{\partial SSE}{\partial \beta} = 0 \Rightarrow -2X^{\mathrm{T}} Y + 2X^{\mathrm{T}} \hat{\beta} X = 0 \tag{11}$$

$$\hat{\beta}_{Pooled} = \left(X^{\mathrm{T}} X\right)^{-1} X^{\mathrm{T}} Y \tag{12}$$

Bringing back the original variables, the estimated vector of parameters is finally given by:

$$\hat{\beta}_{Pooled} = \left[\left(X_{it} - \bar{X}_{it}\right)^{\mathrm{T}} \left(X_{it} - \bar{X}_{it}\right)\right]^{-1} \left(X_{it} - \bar{X}_{it}\right)^{\mathrm{T}} \left(Q_{it} - \bar{Q}_{it}\right) \tag{13}$$

The pooled OLS estimator uses both the between and within variations to estimate the model parameters. Calculation of the sum of squares of within (*SSW*) and between (*SSB*), the following expressions https://byjus.com/anova-formula/ and hence the following equality holds:

$$SSW = \frac{1}{N-1} \sum_{i=1}^{N} \sum_{t=1}^{T} \left(X_{it} - \bar{X}_i\right)^2 \tag{14}$$

$$SSB = \frac{1}{N-1} \sum_{i=1}^{N} \left(X_i - \bar{X}\right)^2 \tag{15}$$

- **Strength:** Pooled OLS should be used to estimate unbiased estimates for specified parameters. It can also be applied to cross-sections to assess the influence of each individual.
- **Weakness:** It is implied that cross-sections and time-step are ignored by pooled least squares since it does not distinguish between various cross-sectional units. Stated differently, it fails to delineate the unique attributes of every cross-sectional unit. in fact, the OLS estimator is biased due to the heterogeneity. The fixed effects model can be used to address this bias problem.

3.2.2. Fixed Effects (FE) Model

The examination of variables that fluctuate over time is aided by this strategy. Nevertheless, the Pooled OLS model mentioned above does not account for this. It's furthered by fixed effects models, which account for individual or cross-sectional differences. By treating α_i as a single fixed effect, it also examines the link between independent variables and dependent factors. That is

$$Q_{it} = \alpha_i + \beta_i X_{it} + \varepsilon_{it} \tag{16}$$

where α_i is an intercept between individuals. It Assumes that the independent variables in this instance are connected to the particular effect of each individual. $\left(X_{i1}, X_{i2}, \cdots, X_{it}; \varepsilon_{i1}, \varepsilon_{i2}, \cdots, \varepsilon_{it}\right) \sim i.i.d$ based on their shared distribution. The X_{it} is exogenous, and its within and between variance is non-zero. Moreover, the correlation between α_i and X_{it} can be any constant number of functions but not zero (Endogeneity is allowed in this case).

Fixed Effects (SSE Estimation)

X_{it} and y_{it} are observed for individuals and periods where $N \geq 2$ and $T \geq 2$. From Equation (16), α_i, β_i stand for unknown parameters and $\left(\varepsilon_{it} \mid X_{it}\right) \sim i.i.d\left(0, \sigma^2\right)$. Estimation of parameter α_i and β_i derived by taking error term in terms of other factors. That is

$$\varepsilon_{it} = Q_{it} - \left(\alpha_i + \beta_i X_{it}\right) \tag{17}$$

Minimizing the sum of the squared residuals of Equation (17) and applying summation on it for N number of individuals and T time steps. Assuming that $\hat{Q}_{it} = \alpha_i + \beta_i X_{it}$, the OLS estimator now becomes:

$$\min_{\alpha_1,\cdots,\alpha_N;\beta_1,\cdots,\beta_N} \sum_{i=1}^{N}\sum_{t=1}^{T}\left[Q_{it} - \hat{Q}_{it}\right]^2$$
$$= \min_{\alpha_1,\cdots,\alpha_N;\beta_1,\cdots,\beta_N} \sum_{i=1}^{N}\sum_{t=1}^{T}\left[Q_{it} - \left(\hat{\alpha}_i + \hat{\beta}_i X_{it}\right)\right]^2$$

In this case, unknown constant α_i and β_i occur in the time step terms(T) of the multiple sum which link to an individual.

$$\min_{\alpha_i;\beta_i} \sum_{t=1}^{T}\left[Q_{it} - \hat{Q}_{it}\right]^2 = \min_{\alpha_i;\beta_i} \sum_{t=1}^{T}\left[Q_{it} - \left(\hat{\alpha}_i + \hat{\beta}_i X_{it}\right)\right]^2 \tag{18}$$

Applying the first order differential conditions on Equation (18) and take its partial derivative with respect to α_i. Assume that $\frac{\partial \varepsilon_{it}^2}{\partial \alpha_i} = 0$ and the following relation holds.

$$-2\sum_{t=1}^{T}\left[Q_{it} - \left(\hat{\alpha}_i + \hat{\beta}_i X_{it}\right)\right] = 0 \tag{19}$$

Dividing -2 at both sides of (19) and distribute the summation yields the following:

$$\sum_{t=1}^{T} Q_{it} - \sum_{t=1}^{T}\hat{\alpha}_i - \sum_{t=1}^{T}\hat{\beta}_i X_{it} = 0 \tag{20}$$

Solving (20) for $\hat{\alpha}_i$ leads to:

$$\sum_{t=1}^{T}\hat{\alpha}_i = \sum_{t=1}^{T} Q_{it} - \sum_{t=1}^{T}\hat{\beta}_i X_{it}$$

$$T\hat{\alpha}_i = \sum_{t=1}^{T} Q_{it} - \sum_{t=1}^{T}\hat{\beta}_i X_{it}$$

$$\hat{\alpha}_i = \frac{\sum_{t=1}^{T} Q_{it}}{T} - \frac{\sum_{t=1}^{T}\hat{\beta}_i X_{it}}{T}$$

$$\hat{\alpha}_i = \bar{Q}_i - \hat{\beta}_i \bar{X}_i \tag{21}$$

The parameters β_i can be estimated by partially differentiating Equation (18). That is

$$\frac{\partial}{\partial \beta_i}\sum_{t=1}^{T}\left[Q_{it} - \hat{Q}_{it}\right]^2 = \frac{\partial}{\partial \beta_i}\sum_{t=1}^{T}\left[Q_{it} - \left(\hat{\alpha}_i + \hat{\beta}_i X_{it}\right)\right]^2 \tag{22}$$

By using (21) in (22) gives the following:

$$\begin{aligned}\frac{\partial}{\partial \beta_i}\sum_{t=1}^{T}\left[Q_{it} - \hat{Q}_{it}\right]^2 &= \frac{\partial}{\partial \beta_i}\sum_{t=1}^{T}\left[Q_{it} - \left(\hat{\alpha}_i + \hat{\beta}_i X_{it}\right)\right]^2 \\ &= 2\sum_{t=1}^{T}\left[Q_{it} - \left(\hat{\alpha}_i + \hat{\beta}_i X_{it}\right)\left(-X_{it}\right)\right] \\ &= -2\sum_{t=1}^{T} X_{it}\left[Q_{it} - \left(\hat{\alpha}_i + \hat{\beta}_i X_{it}\right)\right]\end{aligned}$$

Since

$$\frac{\partial}{\partial \beta_i}\sum_{t=1}^{T}\left[Q_{it} - \hat{Q}_{it}\right]^2 = 0 \tag{23}$$

then

$$-2\sum_{t=1}^{T} X_{it}\left[Q_{it} - \left(\hat{\alpha}_i + \hat{\beta}_i X_{it}\right)\right] = 0 \tag{24}$$

Combining Equations (21) and (24) gives:

$$-2\sum_{t=1}^{T} X_{it}\left[Q_{it} - \left(\bar{Q}_i - \hat{\beta}_i \bar{X}_i + \hat{\beta}_i X_{it}\right)\right] = 0$$

$$\sum_{t=1}^{T} X_{it}\left(Q_{it}-\bar{Q}_i\right)-\hat{\beta}_i\sum_{t=1}^{T} X_{it}\left(X_{it}-\bar{X}_i\right)=0$$

$$\hat{\beta}_i\sum_{t=1}^{T} X_{it}\left(X_{it}-\bar{X}_i\right)=\sum_{t=1}^{T} X_{it}\left(Q_{it}-\bar{Q}_i\right)$$

$$\hat{\beta}_i=\frac{\sum_{t=1}^{T} X_{it}\left(Q_{it}-\bar{Q}_i\right)}{\sum_{t=1}^{T} X_{it}\left(X_{it}-\bar{X}_i\right)} \tag{25}$$

Hence, the above expression (25) is equivalent to:

$$\hat{\beta}_i=\frac{\sum_{t=1}^{T}\left(X_{it}-\bar{X}_i\right)\left(Q_{it}-\bar{Q}_i\right)}{\sum_{t=1}^{T}\left(X_{it}-\bar{X}_i\right)^2} \tag{26}$$

- **Strength:** All of the omitted time-invariant variables are controllable according to the fixed Effects model. As N approaches to infinity and T is fixed, the estimator β turns out to be consistent and unbiased. Every group and every time have a unique intercept in the regression analysis of a fixed-effect model.
- **Weakness:** FE faces challenges in determining the quantity of distinct parameters. It prevents other terms from being attached to the unit error term.

3.2.3. Random Effects (RE) Model

Panel data containing associated interference factors over time and between cross-sections (such as tea factories) will be estimated using the Random Effects (RE) Model. This indicates that it accounts for both these discrete variances and changes that occur over time. It accounts for Heteroscedasticity. unlike the other methods, the sum of square estimates (SSE) is utilised to find the estimator (β), it does not account for the OLS. The covariance of α_i with any of the independent variables X_{it} is assumed to be equal to zero under RE. Furthermore, group time-invariant heterogeneity is unrelated to the error.

Random effects model can be expressed in the following formula:

$$Q_{it}=\alpha_i+\beta X_{it}+\varepsilon_{it} \tag{27}$$

Assume that $\mu=\alpha_i+\varepsilon_{it}$ where μ is the residual presenting the combination of cross section and time series, and α_i stand for the individual residual which is the random characteristic of unit observation. Both error terms have the same mean which is zero. That is $\boldsymbol{E}\left[\alpha_i\right]=\boldsymbol{E}\left[\varepsilon_{it}\right]=0$, and for each expect a different variance (*i.e.* $Var\left[\varepsilon_{it}\right]=\sigma_\varepsilon^2 I$, $Var\left[\alpha_i\right]=\sigma_\alpha^2 I$ which implies that $Var\left[\mu\right]=\sigma_\varepsilon^2 I+\sigma_\alpha^2 I$. For necessary consistency of model, $\boldsymbol{E}\left[X_{it},\alpha_i\right]=0,\forall i,t$. Random Effect model now becomes:

$$Q_{it}=\beta X_{it}+\mu \tag{28}$$

Random Effects (SSE Estimation)

From (28), the residual terms can be given by the following difference:

$$\mu=Q_{it}-\beta X_{it} \tag{29}$$

Once we apply the SSE and BLUE of β we get the following relation:

$$\sum_{j=1}^{N} \mu_j^2 = \mu^{\mathrm{T}} \mu = \left(Q_{it} - \beta X_{it}\right)^{\mathrm{T}} \left(Q_{it} - \beta X_{it}\right) \tag{30}$$

By using the same procedure as used for Equation (11), the random effects estimator for β becomes:

$$\hat{\beta}_{RE} = \left(X^{\mathrm{T}} X\right)^{-1} X^{\mathrm{T}} Y \tag{31}$$

- **Strength:** RE takes into account the time-invariant variables, and it might consider the within and between-group variations. This model can estimate the shrunken residuals.
- **Weakness:** α_i has to be independent of the features. Moreover, it can only detect cross-sectional heterogeneity and not temporal variation in the response variable.

There are three statistical tests that can be used to choose the best model in the panel data model, the Chow test, the Housman Test, and the Lagrange Multiplier test.

Table 2 summarizes and explain typically how to select the best model that fits the data.

Table 2. Panel data model test table.

Types of test	p_value	Selection
Chow test	p_value < 0.05	select FE
	p_value > 0.05	select Pooled OLS
Housman test	p_value < 0.05	select FE
	p_value > 0.05	select RE
Lagrange multiplier	p_value < 0.05	select RE
	p_value > 0.05	select Pooled OLS

3.3. Other Diagnostic Tests on the Data Set

3.3.1. Jarque-Bera Test of Normality

If the data is not normally distributed, we can do some transformations to make it looking closer to following normal distribution. This kind of test will help us to know whether these transformations are needed or not. Jarque-Bera Test of Normality is a statistical test that determines if the skewness and kurtosis of the data are consistent with a normal distribution. It is frequently employed to examine the sample's presumed normalcy. The test statistic, assuming normality as the null hypothesis, has a chi-square distribution. The formula for this test is given by the following relation:

$$JB = \frac{n}{6}\left(S^2 + \frac{1}{4}\left(K-3\right)^2\right) \tag{32}$$

where

JB is the Jarque-Bera test statistic, n is the sample size, S is the sample skewness, and K is the sample kurtosis. If JB is greater than the p_value is less than the chosen significance level, we will reject the null hypothesis of normality.

3.3.2. The Variance Inflation Factor (*VIF*) Test of Multicollinearity

The variance inflation factor (*VIF*) quantifies the extent to which associated predictors raise the variance of an estimated regression coefficient. In particular, the variance of the estimated coefficient when fitting a variable alone is divided by the variance of the estimated coefficient when fitting the variable in the presence of all other predictor variables to determine the variance of the estimated coefficient for each predictor variable. The *VIF* of a given predictor can be calculated as follows:

$$VIF\left(predictor_i\right) = \frac{1}{1 - R_i^2} \tag{33}$$

where

R_i^2 is the constant of determination obtained by regressing the predictor i against all other predictor variables. After calculating *VIF*, the following conditions will help us to decide:

- *VIF* = 1: No correlation between the predictor variable and the other variables.
- *VIF* >1 and <5: Moderate correlation that is generally acceptable.
- *VIF* ≥5: High correlation that indicates potential multicollinearity in the data set.

3.3.3. White's Test of Heteroskedasticity

It is a statistical test that determines if a regression model's residuals have constant variance, which is a fundamental tenet of classical linear regression. This test compares homoskedasticity, or constant variance of errors, against heteroskedasticity, or non-constant variance. Under the null hypothesis of homoskedasticity, it has a chi-square distribution. To determine if the squared residuals' coefficients are jointly statistically significant, the test entails regressing the squared residuals on the model's independent variables. The following is the formula for the White's test statistic:

$$W = nR^2 \tag{34}$$

where n is the sample size and R^2 is the constant of determination from auxiliary regression of squared residuals on the independent variables. To know whether there is homoskedasticity or not, the chi-square distribution with k degrees of freedom is used to compare the test statistic W against the p_value to determine statistical significance.

These tests in Equations (32), (33) and (34) are the three required assumptions of panel data that are prior to any econometric analysis (normality, homoscedasticity and no Perfect Multicollinearity). Violation of one of them, affects the validity of the results and model selection among fixed and random effect models.

4. Results and Discussion

4.1. Data Description

Based on the result provided in Table 3, it highlights that the regression analysis was conducted and F-statistic is of less than 5%, indicating that the model is of a good fit. The R-squared value is 0.666, meaning that the explanatory variables explain 66.6% of the variation in the dependent variable. Looking at the coefficients of the independent variables, both Rainfall and Land coefficients are positive and statistically significant (p-value < 5%); they have a positive impact on tea production while Temperature is statistically significant but with a negative impact on tea output. On the other hand, Fertilizer is not statistically significant (p-value > 5%), but it has a positive impact on tea production. Overall, these results suggest that the explanatory variables included in the regression model explain a substantial portion of the variation in the dependent variable.

Table 3. Ordinary least squares regression results.

		ANOVA Table		
Source	SS	df	MS	Number of obs = 192
Model	4.77037365	4	1.19259341	F(4, 187) = 93.55
Residual	2.38383976	187	0.012747806	Prob > F = 0.0000
Total	7.15421342	191	0.037456615	R-squared = 0.6668
				Adj R-squared = 0.6597
				Root MSE = 0.11291
		Regression Coefficients		
LQit	Coef.	Std. Err.	t	P>|t|
LRainfall	0.2192049	0.0202587	10.82	0.000
LTemp	−2.48979	0.4613697	−0.710	0.000
LLand	0.1465373	0.0404586	3.62	0.000
LFertilizer	0.008486	0.0109398	0.78	0.433
_cons	3.807449	0.199444	19.09	0.000
		95% Confidence Interval		
LRainfall		[0.1792399, 0.2591698]		
LTemp		[1.579631, 3.399948]		
LLand		[0.0667233, 0.2263513]		
LFertilizer		[−0.0130953, 0.0300673]		
_cons		[3.414, 4.200898]		

4.2. Normality Test

This test in Table 4 uses Jarque Bera test and the result is proving the normality in data by giving chi-square of 0.1654 greater than 5%, suggesting that we cannot reject the null hypothesis of normality and our data are normally distributed. It means, we are allowed to go further for analysis without making any data transformations.

Table 4. Jarque-Bera normality test.

Jarque-Bera normality test:	3.599 Chi(2) 0.1654
Jarque-Bera test for H_0:	normality

4.3. Multicollinearity Test

The assumption of multicollinearity was also checked in Table 5. VIF-values are all greater than 1 but less than 5 that shows that there is moderate correlation that are generally acceptable. Therefore, removing one variable will not affect the model. In fact, explanatory variables have independent significant impact on the response variable.

Table 5. Variance inflation factors test for multicollinearity.

Variable	VIF	1/VIF
LTemp	3.20	0.312936
LLand	3.16	0.315989
LFertilizer	1.02	0.976086
LRainfall	1.01	0.988322
Mean VIF	2.10	

4.4. Homoskedasticity Test

Lastly, for the test of heteroscedasticity in Table 6, the test gives chi-square equals 0.957 greater than 5%, suggesting that we cannot reject null hypothesis of homoscedasticity, meaning that there is no heteroscedasticity among the variables. In fact, failing to reject the null hypothesis in this case, gives rise to the explainability of alternative hypothesis.

Table 6. White's test for homoskedasticity.

White's test for Ho: homoskedasticity			
against Ha: unrestricted heteroskedasticity			
	chi2(14)	=	6.35
	Prob > chi2	=	0.9570
Cameron & Trivedi's decomposition of IM-test			
Source	chi2	df	p
Heteroskedasticity	6.35	14	0.9570
Skewness	5.42	4	0.2473
Kurtosis	0.73	1	0.3917
Total	12.50	19	0.8633

4.5. Random-Effects Regression

The result of Random Effects Model (RE) presented in Table 7 highlights the statistical significance of Rainfall with the positive impact on the total production of any tea companies. On the other hand, Temperature, Fertilizer and Land are not statistically significant. Looking on the coefficient of land in the model, it has become neutral variable. You can not mention whether it has a positive or negative effect on the tea production output.

Table 7. Random effects model results.

Random-effects ML regression

Number of obs = 192

Group variable: Company Number of groups = 4

Random effects u_i~ Gaussian Obs per group:

min = 48

avg = 48.0

max = 48

LR chi2(4)	=	100.27
Log likelihood	=	152.153
Prob > chi2	=	0.000

LQit	Coef.	Std. Err.	z	P>|z|	[95% Conf.Interval]
LRainfall	0.214	0.018	11.39	0.000	[0.177, 0.251]
Temperature	−0.154	0.634	0.24	0.807	[−1.088, 0.779]
Land	0.000	0.000	1.61	0.107	[−0.000, 0.001]
Fertilizer	0.026	0.028	0.89	0.373	[−0.030 0.083]
_cons	5.203	0.827	6.29	0.000	[3.581, 6.824]
σ_u	0.105	0.047			
σ_e	1.051	0.050			
ρ	0.502	0.228			

LR test of sigma_u=0:

chibar2(01) = 8.50 Prob ≥ chibar2 = 0.002

4.6. Fixed-Effects Regression

From Fixed-effects regression presented in Table 8, only the variable of interest, which is rainfall, is statistically significant and has a positive impact on tea production across the four different tea companies in the distinct regions of Rwanda. Temperature with negative impact, land with positive effect and rainfall with positive impact.

Table 8. Fixed effects model results.

Fixed-effects (within) regression

Group variable: Company

Number of obs = 192

Number of groups = 4

R-sq:

within = 0.410

between = 0.768

overall = 0.238

corr(u_i, Xb) = 0.055

F(4, 184) = 32.00

Prob > F = 0.000

LQit	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]
LLand	0.030	0.043	0.70	0.483	[−0.055, 0.117]
LFertilizer	0.011	0.010	1.12	0.266	[−0.008, 0.032]
LTemp	−0.370	0.749	−0.50	0.621	[−1.848, 1.106]
LRainfall	0.215	0.019	11.29	0.000	[0.177, 0.252]
_cons	5.370	0.354	15.13	0.000	[4.676, 6.070]
σ_u	0.153				
σ_e	0.106				
ρ	0.677	(F.V due to u_i)			

F test that all u_i=0:

F(3, 184) = 9.36 Prob > F = 0.000

4.7. The Key Finding and Interpretation of Results

Tea output will rise by roughly 0.215 percentage points for every 1 mm increase in rainfall. In Rwanda's Western, Southern, and Northern provinces, rainfall has a positive and statistically significant effect on tea output, referring to the result in FE Model 3 of Table 9. Rainfall is positively correlated with tea output, making it an exogenous variable and a variable of relevance in our model. Overall, this confirms our hypothesis that the rainfall availability affects tea production favourably and is statistically significant. The rest of the results will present tea production and rainfall deterministically and spatially.

Table 9. Fixed Effects Summary where standard errors in parentheses.

VARIABLES	FE Model1	FE Model 2	FE Model 3
LLand	0.019	0.020	0.031
	(0.057)	(0.057)	(0.044)
LFertilizer	0.001	0.001	0.001
	(0.013)	(0.013)	(0.012)
LTemp		−0.418	−0.371
		(0.972)	(0.749)
LRainfall			**0.215*** **
			(0.019)
Constant	**5.779*** **	**5.875*** **	**5.371*** **
	(0.397)	(0.457)	(0.355)
Observations	192	192	192
R-squared	0.001	0.002	0.410
Number of Company	4	4	4

***$p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.8. Time Series

The tea production presented in **Figure 4** demonstrates that Mulindi tea company has surpassed the rest of the tea companies in the production quantity of tons of tea leaves. Contrarily, Nyabihu tea company has recorded the least production output among all the tea Companies that are currently studied. The patterns of tea productions should align with the patterns of rainfall received in respective regions of tea companies. Regardless of the year, it is evident that the tea production records take their local maxima values in the season of MAM, SON and DJF. On the other hand, the tea production takes the minimum value in the season of JJA regardless of the tea company we are talking about.

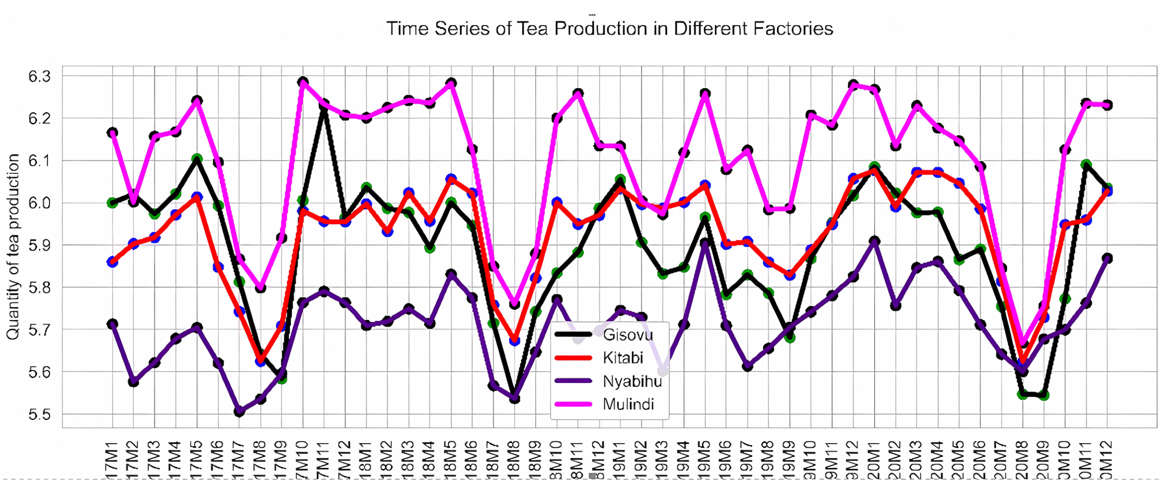

Figure 4. Production patterns in different tea factories/companies.

Tea production time series follows the rainfall patterns on the point of placing the local minima and maxima. Therefore, the observed tea production in **Figure 4** is explained by the result presented in **Figure 5**. In fact, the region that receives the least amount of rainfall is expected to record the least amount of number of tons of the tea leaves that is quantifying the tea production in this study. The more rainfall received, the more tons of tea leaves are plucked in the region.

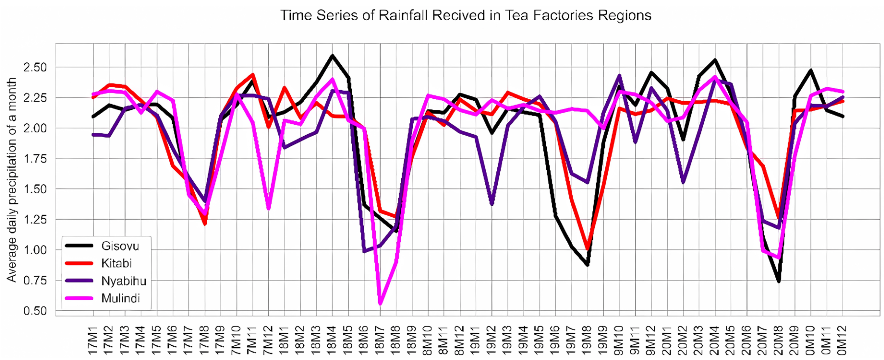

Figure 5. Rainfall patterns in different tea factories/companies.

4.9. Trends in Different Tea Companies

The results in **Figure 6** show that there has been a positive trend in tea production of Nyabihu and Gisovu since January of 2017 till the end of 2020. The data that we are currently analyzing consists of 48 months that makes a total number of 4 years. On the other hand, we realise the negative trend in Kitabi and Mulindi. Although observing positive trends in Nyabihu and Gisovu, Nyahihu has a potential rise in the produced amount of tons of tea leaves. Moreover the potential fall in the produced tons of tea leaves is evident in Kitabi compared to the neighbour in production as Mulindi was confronted by a gently sloping trend.

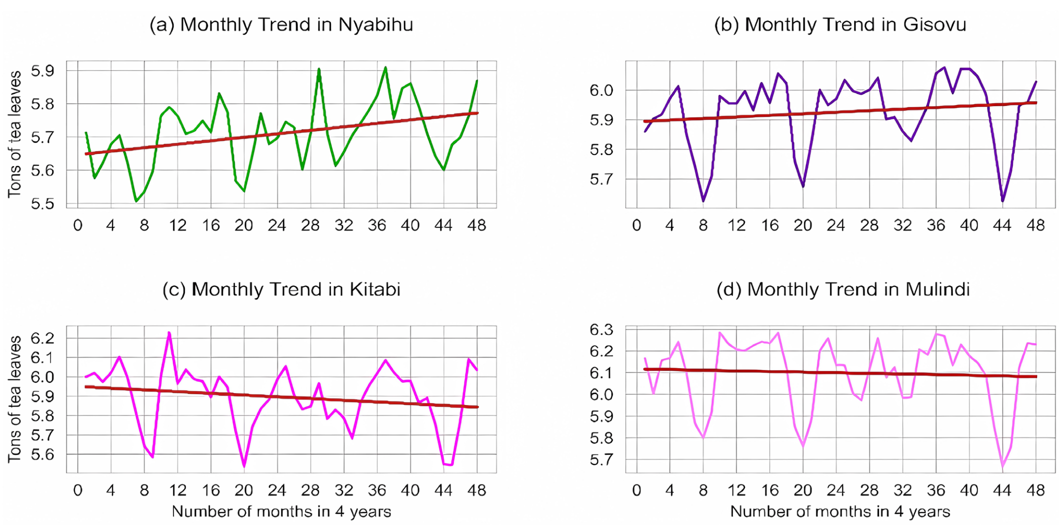

Figure 6. Production trends.

4.10. Monthly Tea Production by Year and Tea Company

Regardless the year and month we are talking about, Mulindi production was always on the top of the table. If you consider the results in Figures 7-10, you realize that Gisovu production was the second top ranked tea production company. Since 2018, Kitabi tea company has overtaken the records of Gisovu tea company and become the second top ranked tea production company in the four considered companies. It does not matter which year or month we are considering, Nyabihu tea company was always on the bottom of the table hence becoming the least tea production company in this study.

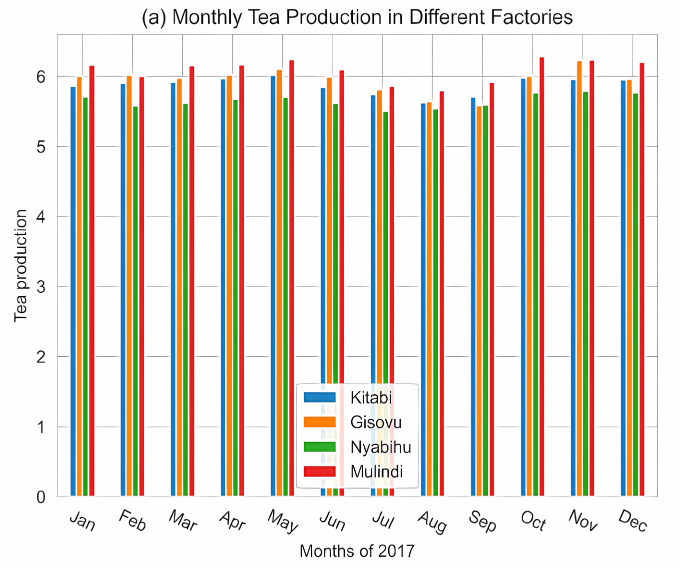

Figure 7. 2017.

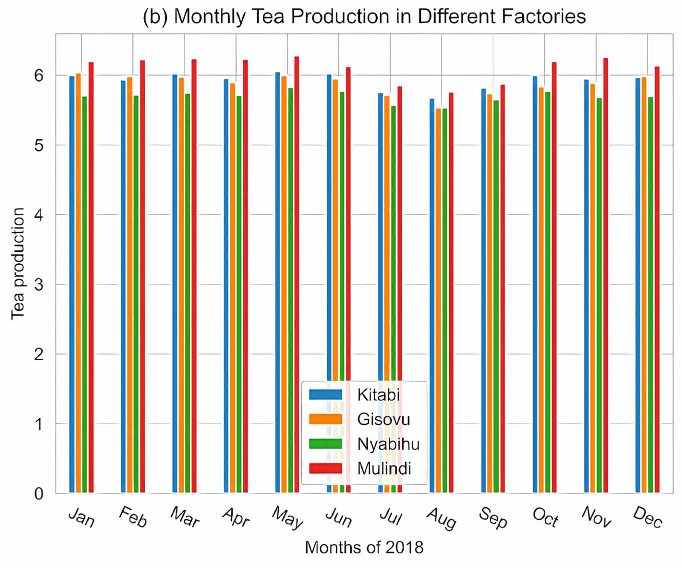

Figure 8. 2018.

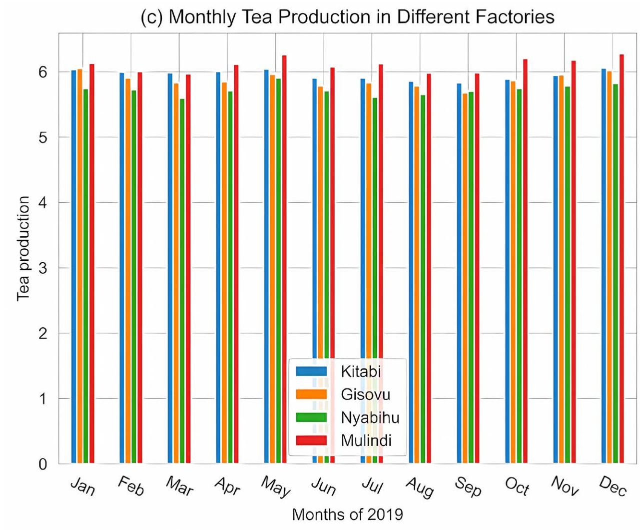

Figure 9. 2019.

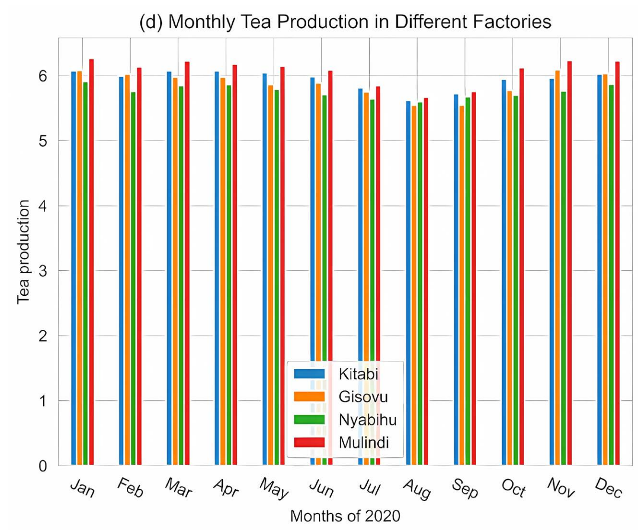

Figure 10. 2020.

4.11. Comparison of Total Tea Production

From Figure 11 and Figure 12, Gisovu was the second-top-ranked tea production company in 2017. Although Kitabi has overtaken Gisovu in 2018 and 2019, these two companies show a very small difference in their production records. This is due to the fact that these companies are situated relatively close, hence receiving almost the same amount of rainfall. Regardless the year, Mulindi tea company has recorded the best tea production among the four companies. On the other hand, Nyabihu was always recording the lowest values compared to the remaining tea companies.

The cumulative tea production presented in Figure 13 of 4 distinct tea companies has reached to 1134.3 tons of the tea leaves plucked from Mulindi (292.8 tons), Kitabi (284.4 tons), Gisovu (283 tons) and Nyabihu (274.1 tons). We noticed that Mulindi tea company is the major contributing company to the total production calculated over four years. Being the major contributing company is attributed to the amount of received rainfall in the region of its tea plantation.

Figure 11. Yearly production.

Year	Kitabi	Gisovu	Nyabihu	Mulindi
2017	70.5	71.3	67.9	73.1
2018	71.2	70.5	68.4	73.4
2019	71.4	70.5	68.7	73.3
2020	71.3	70.6	67.1	72.9

Figure 12. Production values in tons.

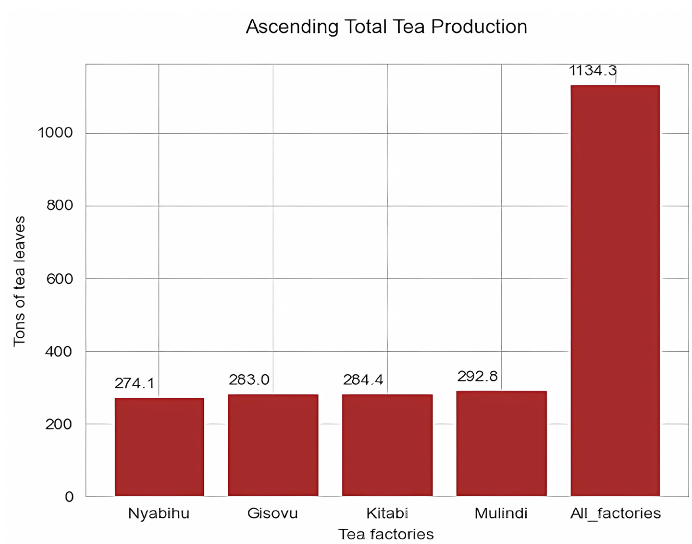

Figure 13. Comparison of production.

4.12. Percentage Contribution

The chart in Figure 14 describes the percentage contribution of a specific tea company in the total production recorded over four years with Mulindi taking a lead with 25.8%. Other tea companies such as Kitabi, Gisovu and Nyabihu have contributed 25.1%, 24.9% and 24.2% respectively. This result is complementary to the result presented in Figure 5.

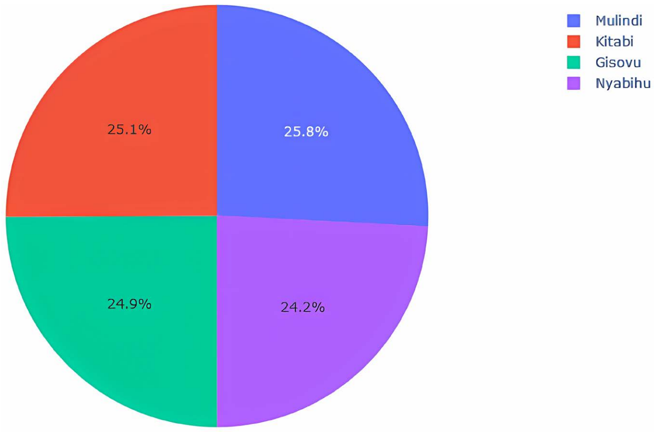

Figure 14. Contribution of a tea company in the total production observed.

4.13. Proportionality of Influence of Rainfall on Tea Production

It is clear that the total received rainfall has impacted the total tea production in the tea companies. Evidently, the major contribution of Mulindi to the total production accumulated over four years is directly proportional to the rainfall received of about 96.22 mm surpassing the rest of the companies. There is a slight difference between the rainfall received in Kitabi and Mulindi but that difference has created a notable difference in the observed total tea production. In fact, if we consider the two companies which have planted the tea on the same area but receiving distinct amount of rainfall, the tea production shall be distinct as well. The result in Figure 5 is motivated by the result in Figure 15 while the result in Figure 4 is motivated by the result in Figure 16.

4.14. Climatological Characteristics of the Seasons in Rwanda

The climatology of Rwanda shows that the season of MAM receives large amount of precipitation, followed by SON. The season of DJF is also wet but comes after SON. Lastly, JJA seems to be dry almost everywhere across the country. The wetness of a specific region plays a significant role in observed tea production. The tea companies were not randomly placed in the Northern, Western and Southern provinces. These provinces normally receive a large amount of rainfall, hence building confidence in investors to plant tea in the regions, which is expected to cover the return on investment in a short period of

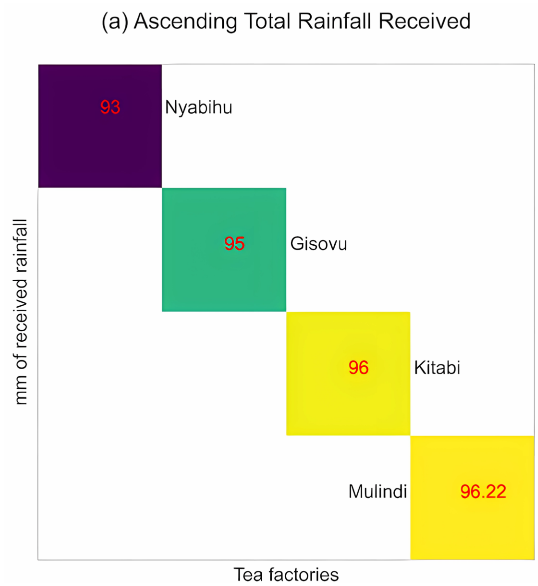

Figure 15. Total Rainfall in tea company region.

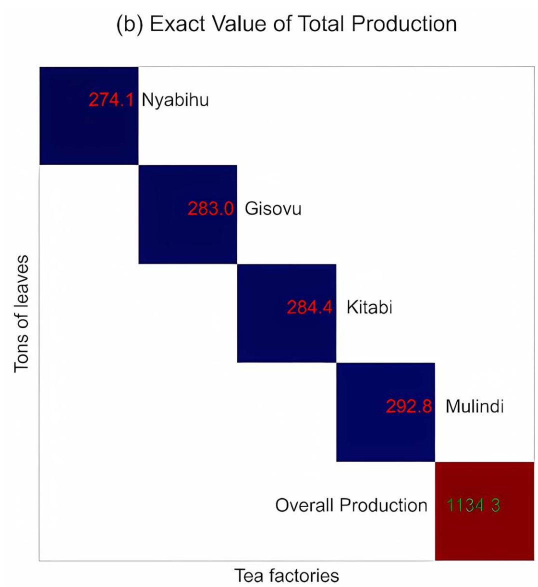

Figure 16. Total production of each tea company.

time. The rainfall intensity increases westwards due to topographical nature of the country, while surface temperature increases Eastwards. Moreover, there is thick vegetation cover around the region of tea companies. Nyungwe forest is closer to both Kitabi and Gisovu whereas Virunga National Park is closer to Mulindi. Furthermore, tea companies such as Gisovu and Nyabihu are closer to the biggest lake in Rwanda (Kivu lake). The Eastern province is naturally made of lowlands, whereas the Northern and Western provinces are so hilly, especially the volcanic mountains that are all found in the Northern province. This also adds information on the results obtained in the results of figures such as 5, 13, 15 and 16. The season that records the local minima and global minimum of tea production was JJA, this is attributed to the dryness of the regions due to climatology. It is evident that JJA is not receiving the precipitation of 1 mm/day on average. Therefore, MAM season would record the global maximum of the total production across the different tea production companies. In fact, climate variables such as precipitation and surface temperature are interdependent. The rise of temperature today will affect the amount of rainfall that will be received in the upcoming season.

4.15. Interdependence of Climate Variables

The results in Figure 17 and Figure 18 are informed by the result in Figure 19 and links the critical understanding of possible cause of observing the patterns in time series of the result 4 that associates it with results 5, and 16. Figure 19 explains that the potential rise in one variable today is responsible of causing a potential fall in the other and this fluctuation influence is chronologically propagated.

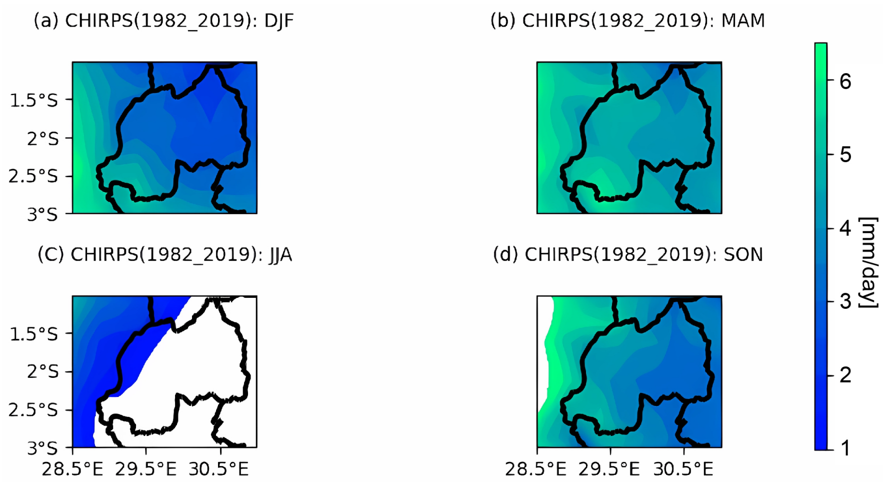

Figure 17. Seasonal variation in received rainfall.

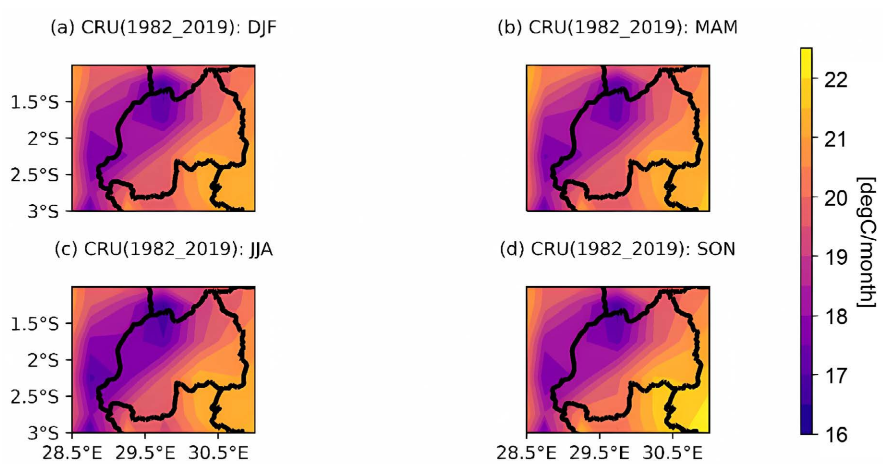

Figure 18. Seasonal variation in surface temperature.

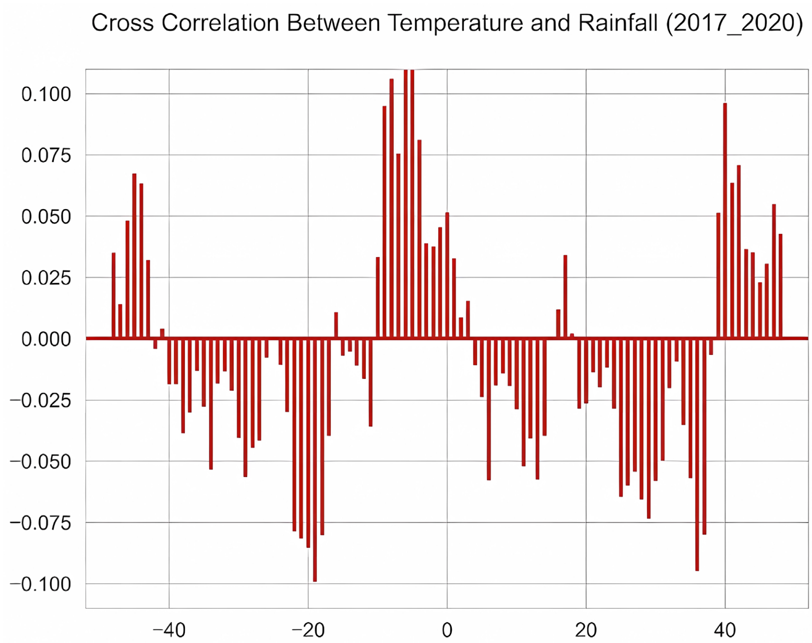

Figure 19. Cross correlation between climate variables considered.

5. Conclusions and Policy Implication

From the study findings, it is evident that climate variability and change pose a direct influence to tea production in Rwanda. The change in rainfall patterns can have a direct impact on tea production, whereas unfavourable temperatures expose tea farmers to climate risk, leading even to lower production because of their negative effect on tea output, but this has a certain level of insignificance. Plot size (Land) and Fertilizer, as agricultural inputs, also have a positive impact on tea production, but this positive impact may be in vain if erratic nature of rains persists.

The dependence of tea production on climate variables creates a need for collaborative efforts towards developing definite, viable, and sustainable adaptation and mitigation options targeting tea farming. In addition, despite the challenges posed by climate change, the government needs to ensure that tea policy reforms are targeted towards raising the competitiveness of Rwandan tea on the local and global markets and that tea prices, bonuses, and prime tea production insurance are also paid on time.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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