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CLIMATE CHANGE IMPACTS ON REGIONAL ECONOMICS IN SOUTH ASIA

Impacts of climate change on paddy yields in different climatic zones of Sri Lanka: a panel data approach

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Abstract
While climate change affects agricultural production globally, scarce literature has quantified the impacts of climatic factors on paddy yields with attention to specific water regimes, climatic zones, growth periods, and crop seasons. This study aimed to identify the effects of various climatic variables at different plant growth phases (growing and harvesting), crop seasons (Maha and Yala) [In Sri Lanka, there are two main crop seasons. Maha is the major cultivation season covering the months of October to March, and Yala is the minor cultivation season covering the months of April to September], and water regimes (major irrigation, minor irrigation, and rainfed) in three climatic zones (dry zone, intermediate zone, and wet zone) of Sri Lanka. A district-wise annual panel dataset was constructed for a 39-year period (1981 to 2019) covering 18 districts and analyzed by panel regression methods. The results showed that temperature had significant non-linear effects on yields in the dry and intermediate zones. Variation in temperature decreased yields more in the dry zone than in other zones. Rainfall significantly reduced yields in the dry and wet zones, whereas it increased yields in the intermediate zone. Rainfall fluctuations decreased yields in the wet zone more than in other zones. These findings suggest a need for dissemination of climate-smart agriculture practices by considering the characteristics of each water regime, particularly in the dry zone. For rainfed paddies, a crop insurance scheme should be introduced to reduce crop losses due to harsh climatic events. Complementary policies, such as improvement of irrigation systems and provision of timely weather forecasts, can support smallholder paddy farming.

Keywords Climatic zone · Major irrigation · Minor irrigation · Rainfed · Panel regression · Rainfall · Temperature · Variability

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1 Introduction

Climate variability affects food security by contributing 60% of yield variability around the world (Matiu et al. 2017). Climate change in the forms of rising temperature and unpredicted rainfall is expected to adversely affect agricultural production including rice (*Oryza sativa* L.) (Kumar and Sharma 2013; Marambe et al. 2014; Ministry of Mahaweli Development and Environment 2016; Rahman et al. 2017; Jayawardena et al. 2018). Each crop exhibits a specific range of optimal temperature and rainfall during the growth stages to maximize its yields (Mohanty et al. 2013; Chowdhury and Khan 2015). Variation in temperature may cause shortened duration of the growing phase, rice flower sterility, and pest and disease outbreaks. On the other hand, rainfall fluctuation as characterized by drought, flood, and erratic rainfall patterns significantly diminishes crop yields (Marambe et al. 2014; Esham et al. 2018). Thus, climate change is a major cause of crop failures, poverty, and food insecurity (Kumar and Sharma 2013; Marambe et al. 2014; Esham et al. 2018). The sensitivity of crop yields to phase-specific temperature and rainfall varies geographically (Gourdji et al. 2013; Ahmad et al. 2021). If climate variability continues to increase, there is a need to understand the responses of paddy yields to changes in temperature and rainfall at the macroeconomic scale to inform policies geared towards sustainable development (Gumel et al. 2017; Matiu et al. 2017).

According to the Global Climate Risk Index 2017, Sri Lanka was considered as one of the countries mostly affected by climate change (Ministry of Mahaweli Development and Environment 2016; Eckstein et al. 2018). Sri Lanka is an island located in the tropical zone of the Indian Ocean, frequently affected by climatic events (Ministry of Mahaweli Development and Environment 2016). The agricultural sector contributed 7% to the Gross Domestic Product in 2020 (Central Bank of Sri Lanka 2020) and utilized 45.5% of the total land area (World Bank 2022), and 25.1% of the national workforce (Department of Census and Statistics 2020), catered to nearly 80% of the domestic food requirements and generated 70% of the income for rural population (Institute of Policy Studies 2015).

Among various crops, paddy accounts for the largest crop area and is the main staple in the Sri Lankan cuisine, produced across various agroecological landscapes of the country. Sri Lanka is nearly self-sufficient in rice consumption, and paddy contributed 0.8% to the Gross Domestic Product in 2020 (Central Bank of Sri Lanka 2020). Besides paddy, Sri Lanka is well known for its production of tea, rubber, coconut, and fruits (Thibbotuwawa and Hirimuthugodage 2015).

Global warming and climate variability affect the hydrological cycle and the irrigation demand in crop production (Kamruzzaman et al. 2020), whilst the weather patterns exhibit spatiotemporal variations (Gourdji et al. 2013; Ahmad et al. 2021). Further, climate impacts on crop yields differ by water supply systems (FAO 1997; Tsusaka and Otsuka 2013a) and the growth phase of the plant (Yoshida 1981; Ahmad et al. 2021). Although literature is loaded with assessment of climate change impacts on agriculture globally, limited studies have disaggregated such impacts by plant growth phase, crop season, water supply system, and climatic zone.

The objective of this study was to quantitatively assess the effects of key climatic variables (i.e., temperature and rainfall), capturing both endowments and changes, on paddy yields in different spatial (climatic zones and water regimes) and temporal (crop seasons and plant growth phases) spheres in Sri Lanka. The output of this study provides policy makers research-based evidence in formulating climate adaptation measures for the agricultural sector of Sri Lanka and beyond.

2 Impacts of climate change on paddy yields

Due to the high exposure of agriculture to weather conditions, climatic factors directly affect agricultural production (Kumar et al. 2004; Kumar and Sharma 2013; Kukal and Irmak 2018). Numerous studies have assessed the effects of climate change on paddy yields, and the results vary from place to place due to the differences in rice varieties, topography, soil conditions, and the severity of climate change (Ray et al. 2015; Ara et al. 2017; Matiu et al. 2017; Amarasingha et al. 2018). Table 1 summarizes the key literature on climate change impacts on paddy yields. Rising temperature during the crop growth season positively affected paddy yields at higher altitudes of the Koshi River basin in Nepal (Bhatt et al. 2014), whereas a negative effect on paddy yields was observed in most of India (Kumar and Sharma 2013), Bangladesh (Chowdhury and Khan 2015), Vietnam (Le 2016), Northern Togo (Ali 2018), and at lower altitudes of the Koshi River basin in Nepal (Bhatt et al. 2014). On the other hand, an increase in temperature during the crop growth season did not exert significant effects on paddy yields in the Philippines (Peng et al. 2004), paddy producing areas of Nepal (Devkota and Paija 2020), and Surinam (Riad and Peter 2017).

An increase in rainfall exerted positive effects on paddy yields in Nepal (Devkota and Paija 2020), spring and autumn yields in Vietnam (Le 2016), and *aus* (pre-monsoon rice, rainfed) and *aman* (monsoon-season rice, rainfed) yields in Bangladesh (Chowdhury and Khan 2015; Mamun et al. 2015), whereas negative effects were noted in India (Kumar and Sharma 2013), northern Togo (Ali 2018), and *boro* (dry-season/winter rice, irrigated) yields in Bangladesh (Ara et al. 2017), and no significant effect in Nigeria (Tiamiyu et al. 2015). Kaur and Attwal (2017) observed that in India, less rainfall during the maturity phase led to higher paddy yields, while rainfall during other phases did not affect paddy yields (Ray et al. 2015; Li and Troy 2018).

Current literature on the impacts of climate change on paddy yields in Sri Lanka shows mixed results. Mathanraj and Kaleel (2016) found that in Eastern Province, higher rainfall positively affected paddy yields during the Maha season (major season from October to March), whereas it had no effect during the Yala season (minor season from April to September). Both negative and positive effects of extreme rainfall depending on the climatic zone have been reported (Sujeewa 2011; Chithranayana and Punyawardena 2014; Wickramagamage 2016; Esham et al. 2018). Furthermore, according to Walisinghe et al. (2017), an increase in temperature solely or in combination with changing rainfall had negative effect on paddy yields in the wet and dry zones. These studies indicate that the impacts of climatic factors on crop

Table 1 List of key literature on climate impacts on paddy yields

Climate variable	Direction of effects	Study site	Literature
Rising temperature	Positive effects	Higher altitudes of the Koshi River basin in Nepal	Bhatt et al. (2014)
	Negative effects	India	Kumar and Sharma (2013)
		Bangladesh	Chowdhury and Khan (2015)
		Vietnam	Le (2016)
		Northern Togo	Ali (2018)
		Lower altitudes of the Koshi River basin in Nepal	Bhatt et al. (2014)
		Temperature shows negative effects on paddy yield in short run and in long run the effects fade in India	Kumar et al. (2021b)
		Mean temperature shows negative effects on paddy yield in long run and in short run positively affects in India	Baig et al. (2022)
		Punjab in India	Bhardwaj et al. (2022)
		Lower middle-income countries	Kumar et al. (2021a)
		Sichuan Province, China	He et al. (2022)
	No effects	Philippines	Peng et al. (2004)
		Paddy producing areas of Nepal	Devkota and Paija (2020)
		Surinam	Riad and Peter (2017)
Increasing rainfall	Positive effects	Nepal	Devkota and Paija (2020)
		Spring and autumn yields in Vietnam	Le (2016)
		Aus (pre-monsoon rice, rainfed) and *aman* (monsoon-season rice, rainfed) yields in Bangladesh	Chowdhury and Khan (2015) and Mamun et al. (2015)
		Lower middle-income countries	Kumar et al. (2021a)
		Rainfall shows positive effects on paddy yield in short run and in negative long run impact in India	Kumar et al. (2021b)
		Sichuan Province, China	He et al. (2022)
	Negative effects	India	Kumar and Sharma (2013)
		Northern Togo	Ali (2018)
		Boro (dry-season/winter rice, irrigated) yields in Bangladesh	Ara et al. (2017)
		Punjab in India	Bhardwaj et al. (2022)
	No effects	Nigeria	Tiamiyu et al. (2015)

growth performance vary by the climatic zone and the crop season. However, influence of climate change on paddy yields under different water regimes and at different phases of plant growth remains largely unknown in Sri Lanka. Use of season-wise or growth phase-wise weather variables instead of annual averages would be useful to obtain reliable implications, as suggested by Le (2016), Kukal and Irmak (2018), and Silungwe et al. (2019). Literature also mentioned a need for studies incorporating the different climatic zones in Sri Lanka (Osborne and Wheeler 2013; Marambe et al. 2014; Kukal and Irmak 2018).

3 Materials and methods

3.1 Study area

Sri Lanka has three major climatic zones, namely the dry zone, intermediate zone, and wet zone under which 46 agroecological regions are defined (Department of Survey 2007; Amarasingha et al. 2018). The dry zone is characterized by an annual rainfall below 1750 mm and an average temperature nearly 28 °C. The intermediate zone has an annual rainfall in the range of 1750 to 2500 mm and temperature ranging from 24 to 26 °C. The wet zone has an annual rainfall above 2500 mm and an average temperature of approximately 24 °C (Punyawardena 2007). Rice is grown across the climatic zones that offer different timings and lengths of the growth period. In general, paddy is cultivated twice a year, namely Maha season and Yala season, relying on northeast and southwest monsoons, respectively (Punyawardena 2007). The total area planted with paddy was 730,000 ha in the Maha season and 400,000 ha in the Yala season in 2020 (Department of Census and Statistics 2021a).

Each season can be further divided into the following two phases: the growth phase (growth and reproductive stages) and the harvest phase (grain ripening and harvesting stages) (Yoshida 1981; Auffhammer et al. 2011). The Yala growth phase is from April to June; the Yala harvest phase is from July to September; the Maha growth phase is from October to December; and the Maha harvest phase is from January to March (Leaker 1984).

There are mainly three types of water regimes under which paddy cultivation is practiced as follows: major irrigation, minor irrigation, and rainfed farming. Major irrigation refers to the land area that is irrigated by tanks with a capacity to serve more than 80.94 ha. Irrigation systems with a smaller capacity than this are deemed as minor irrigation (Department of Census and Statistics 2018). The tank-based irrigation system in the dry zone of Sri Lanka is one of the oldest irrigation systems in the world (Abeywardana et al. 2019). Utilization of major irrigation tanks is regulated by the Irrigation Department, while minor irrigation schemes are managed by both regional offices and farmer organizations (Abeywardana et al. 2019). According to the recent statistics by the Department of Census and Statistics (2021a), the total area of lowland paddy fields was 890,000 ha, with 400,000 ha under the major irrigation regime, 240,000 ha under the minor irrigation regime, and 250,000 ha under the rainfed regime.

This study covered eight districts (Anuradhapura, Polonnaruwa, Ampara, Baticcaloa, Trincomalee, Mannar, Hambantota, and Puttalum) in the dry zone, three (Kurunagala, Monaragala, and Badulla) in the intermediate zone, and seven (Colombo, Kalutara, Galle, Matara, Kandy, Nuwara Eliya, and Rathnapura) in the wet zone (Fig. 1).

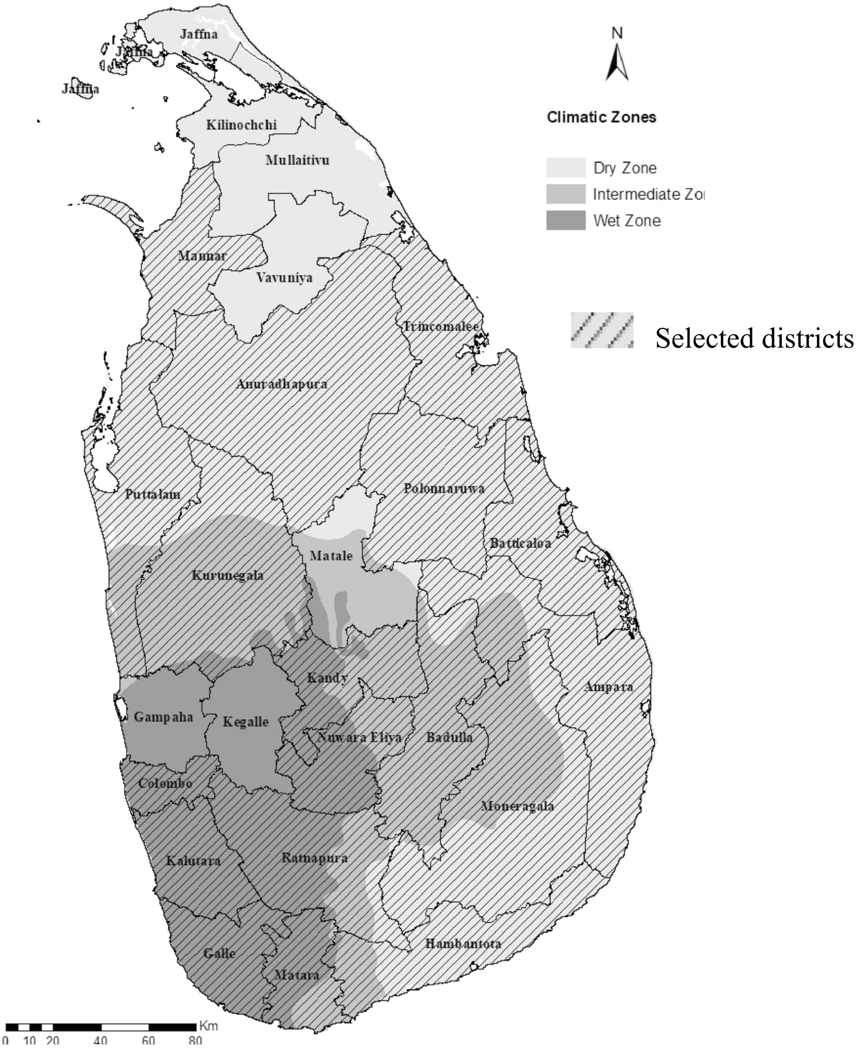

Fig. 1 Districts included in the analysis across the three climatic zones of Sri Lanka. *Source*: Adapted from the Department of Survey (2007)

3.2 Data

A panel dataset was constructed by covering 39 years from 1981 to 2019 and 18 districts out of the 25, lying across the three climatic zones of Sri Lanka. The selected districts were the most relevant in terms of paddy production and data availability for the key variables of interest. Data for paddy yields (harvest, kg/ha) from the three water regimes and the two seasons were obtained from the Department of Census and Statistics, Sri Lanka. Daily climate data (maximum temperature and rainfall) were obtained from the meteorological stations of the Department of Meteorology and the Department of Agriculture for the period of 1981 to 2019. Daily climate data were then aggregated into the four phases of the year (Yala growth phase, Yala harvest phase, Maha growth phase, and Maha harvest phase) as defined above in Sect. 3.1. Daily maximum temperature was averaged over days during each growth period, while the summation of daily rainfall was obtained for the same growth period. Table 2 shows the meteorological stations in each district and their elevation.

Additionally, a couple of covariate variables were collected for inclusion into the analysis to minimize the omitted variable bias in the estimation of the climate effects. Inclusion of population density is a relevant process as positive effects would support the induced innovation theory (Hayami and Ruttan 1971; Tsusaka and Otsuka 2013a), which portrays the effects of population density on labor availability for agriculture and relative factor prices, thereby affecting agricultural productivity (Josephson et al. 2014). The Department of Census and Statistics (2021a)

Table 2 Meteorological stations in the coverage of this study. *Source*: Abeysekera et al. (2017)

Climatic zone	District	Station	Elevation (m)
Dry zone	Puttalum	Puttalum	2.1
	Baticcaloa	Baticcaloa	2.7
	Ampara	Pothuvil	3.6
	Mannar	Mannar	3.6
	Hambantota	Hambantota	15.5
	Trincomalee	Trincomalee	79.0
	Anuradhapura	Anuradhapura	92.5
	Polonnaruwa	Aralaganwila	230.0
Intermediate zone	Kurunagala	Kurunagala	116.1
	Monaragala	Monaragala	146.0
	Badulla	Bandarawela	1219.0
Wet zone	Kalutara	Bombuwela	3.0
	Colombo	Colombo	7.3
	Galle	Galle	12.5
	Matara	Labudoowa	9.0
	Rathnapura	Rathnapura	34.4
	Kandy	Peradeniya	487.6
	Nuwara Eliya	Nuwara Eliya	1894.0

reports positive relation between farm size (which is affected by population density in predominantly agricultural areas) and crop yield in Sri Lanka, though it tends to be the opposite in developing countries in general. Moreover, relative land scarcity to population tends to induce innovations that enhance productivity (Tsusaka and Otsuka 2013a, b; Rahman et al. 2017; Chandio et al. 2022). Yearly population density was calculated by interpolating the population census data obtained from the Department of Census and Statistics. Fertilizer availability is a key factor for yield variations. Although historical fertilizer quantity data for paddy production was absent, the presence of government fertilizer subsidy would represent fertilizer availability. The fertilizer subsidy was applied nation-wide and did not vary spatially. Information on season-wise availability of fertilizer subsidy for the three main fertilizer types (urea, triple superphosphate, and muriate of potash) was obtained from the Department of Agriculture.

3.3 Statistical analysis

The study employed descriptive and econometric analyses. Descriptive statistics of the climate variables were presented for each growth phase, season, and climatic zone. The trend in the climate variables were verified by the Mann-Kendal test, Sen's slope, and linear regression (Asare-Nuamah and Botchway 2019; Bhatt et al. 2019; Gadedjisso-Tossou et al. 2021). Seasonal yield differences were assessed by the *t*-test for each climatic zone. The trends in temperature, rainfall, and paddy yields were graphically illustrated for each climatic zone to better reflect the overall context.

A large body of literature adopted panel regression for measuring climate change impacts on crop yields (Kumar et al. 2004; Osborne and Wheeler 2013; Bhatt et al. 2014; Singh et al. 2014; Doğan and Kan 2019). There are mainly the following three variants of models for statistical analysis of panel data: the pooled OLS (ordinary least squares), fixed effect (FE) model, and random effect (RE) model (Gujarati 2007; Lobell and Burke 2010). The pooled OLS uses the OLS regression without specifying the cross-sectional observational unit identifiers, thereby not utilizing the panel data structure (Hiestand 2005). This model requires the strong assumption that there is no unobservable time-invariant heterogeneity among the cross-sectional units. The model is thus most suitable when the dataset lacks the panel structure and contains different sets of cross-sectional units between points in time, which is commonly the case with census data but not with district-wise data. It is also relatively appropriate when the number of time points is few in panel data. On the other hand, the FE model controls for the unobservable time-invariant district-specific heterogeneity (e.g., soil type, topography, ethnic practices, infrastructure), which would otherwise cause severe estimation biases in the estimated climate effects, such as the endogeneity bias (Nwakuya and Ijomah 2017). The RE model assumes that the district-specific heterogeneity is represented by a random variable that is uncorrelated with the covariates, which is not a requirement for the FE model. The advantage of the RE model is that the RE estimators are more efficient (i.e., more statistical power) than the FE estimators and that the RE model can explicitly include time-invariant independent variables, which are absorbed and cannot be analyzed by the FE model. The RE model is categorized as one of the generalized least squares methods, while the FE model is equivalent to the ordinary least squares with dummy variables representing the districts. To determine between the two models, the Hausman test was employed. The null hypothesis of the Hausman test is that the error terms are uncorrelated with the independent variables. If the null hypothesis is not rejected ($p > 0.10$), the RE can be used. Otherwise, the FE has to be adopted, including the case where the Hausman test fails to achieve model convergence.

This study employs the following functional form and the variables specification for each climatic zone, each growth phase, and each water regime:

$$Y_{ijstw} = \beta_0 + \beta_1 T_{ijst} + \beta_2 T_{ijst}{}^2 + \beta_3 D.T_{ijst} + \beta_4 \mathrm{Rf}_{ijst} + \beta_5 \mathrm{CVRf}_{ijst} + \beta_6 \mathrm{WD}_{ijst} + \beta_7 \mathrm{PD}_{it} + \beta_8 \mathrm{Fert}_{it} + \beta_9 S_{it} + \sum_{k=1}^{m} \alpha_k \mathrm{Year}_{kt} + u_{ijsw} + \varepsilon_{ijstw} \tag{1}$$

where Y_{ijstw} represents paddy yield in kg/ha for the ith district, growth phase j (growing phase or harvesting phase), season s (Maha or Yala), year t, and water regime w (major irrigation, minor irrigation, or rainfed); T_{ijst} is the mean of daily maximum temperature in °C, Rf_{ijst} is rainfall in mm, WD_{ijst} is the number of wet days (days with more than 1 mm daily rainfall). Climate variability is represented by two variables: CVRf_{ijst} represents fluctuation in daily rainfall during the growth phase and $D.T_{ijst}$ represents temperature anomaly as the absolute difference from the previous year for the same phase. As temperature typically exhibits non-linear effects on crop yields (Rowhani et al. 2011; Tsusaka and Otsuka 2013a), the square term of temperature ($T_{ijst}{}^2$) was included. Population density (PD_{it}) and the fertilizer subsidy dummy (Fert_{it}) were included as district-level covariates to minimize the estimation bias. The seasons were included in the form of the Maha season dummy (S_{it}). A series of year dummies (Year_{kt}) for $k = 1982$ to 2019, with the base year 1981, were included to absorb any year-specific external shocks. To keep the result tables succinct, α_k were dispensed within the result section; yet, the full tables are available in the Supplementary Material, The set of β are the coefficients to be estimated, u_{ijsw} represents the unobservable time-invariant district-specific heterogeneity, and ε_{ijstw} is the random error term. Table 3 presents the variables included in the models, a priori signs of the estimated coefficients, and related literature. Kernel density plots for paddy yields by water regime, season, and climate zone were obtained to assess the distribution of the dependent variable.

In general, the β coefficients represent the marginal effects of the independent variables on paddy yields, which is the average change in yield when each independent variable increases by one unit or when the dummy variable changes from zero to one, holding other variables unchanged. The exception is temperature for which the marginal effect is represented by Eq. (2).

$$\text{Marginal effect of temperature on yield} = 2 * \beta_2 * T + \beta_1 \tag{2}$$

As the effect is non-linear, it depends on the level of temperature. This also enables us to estimate the optimum temperature at which paddy yields are maximized, through the following formula (Bambaranda et al. 2019).

Table 3 The variables, their measurements, a priori signs, and relevant literature

Symbol	Variable	Definition	Measurement	A priori sign	Literature
Y_{ijstw}	Paddy yield	Yield of water regime w (major irrigation, minor irrigation, and rainfed) for district i, growth phase j, season s, year t	kg/ha	N/A	
T_{ijst}	Temperature	Mean of daily maximum temperature over each growth phase	°C	+/–	Bhatt et al. (2014), Afzal et al. (2017) and Adhikari et al. (2017)
${T_{ijst}}^2$	Squared temperature	The square term for T_{ijst}	$(°C)^2$	–	Bhatt et al. (2014), Adhikari et al. (2017) and Ali (2018)
$D.T_{ijst}$	First difference in temperature	Absolute change in mean maximum temperature for each growth phase from the previous year	°C	–	Osborne and Wheeler (2013), Adhikari et al. (2017) and Ali (2018)
Rf_{ijst}	Rainfall	Total rainfall during each growth phase	mm	+/–	Bhatt et al. (2014), Ali (2018) and Doğan and Kan (2019)
CVRf_{ijst}	Fluctuation in rainfall	Coefficient of variation for daily rainfall over the three-month growth phase	%	–	Rowhani et al. (2011), Ara et al. (2016) and Ali (2018)
WD_{ijst}	Number of wet days	The number of wet days (more than 1 mm a day) during each growth phase	Days	+	Ara et al. (2016), Ali (2018) and Silungwe et al. (2019)
PD_{it}	Population density	Annual population density per district	Persons/km^2	+	Auffhammer et al. (2011), Tsusaka and Otsuka (2013b) and Khanal et al. (2014)
Fert_{it}	Fertilizer subsidy dummy	A dummy variable for availability of fertilizer subsidy	1 if fertilizer subsidy is available; 0 otherwise	+	Tsusaka and Otsuka (2013b) and Kumar and Sharma (2013)
S_{it}	Season	A dummy variable indicating the season	1 if Maha; 0 if Yala season	+	Rowhani et al. (2011) and Bhatt et al. (2014)
Year_{kt}	Year	A set of dummy variables for each year k (k = 1982–2019)	1 if the observation was in year k; 0 otherwise (base year: 1981)	+/–	Walisinghe et al. (2017)

$$\text{Optimum temperature} = -\frac{\beta_1}{2 * \beta_2} \tag{3}$$

The variance inflation factor (VIF) was obtained to examine the possibility of high multicollinearity, excluding the squared term. In the growing phase equation, WD_{ijst} showed the VIF greater than 10 through collinearity with Rf_{ijst}. Therefore, WD_{ijst} was excluded for j = growing phase. Otherwise, all the variables showed the VIF smaller than 5 and were thus included. In order to correct for heteroskedasticity and correlation across time, robust standard errors with non-zero covariances at the district level (i.e., clustered standard errors) were used. Additionally, sensitivity analysis was performed considering 90% confidence interval (i.e., 5 and 95 percentile) to show the upper and lower boundary values of the coefficients. The data were analyzed using STATA version 17.

4 Results

4.1 Descriptive statistics

4.1.1 Climatic variables

Table 4 presents the climatic characteristics in the Yala and Maha seasons by growth phase by climatic zone for the entire study period. The highest mean temperature was observed in the growing phase of the Yala season in the dry zone (33.38 °C), whereas the lowest mean temperature was observed in the harvesting phase of the Yala season in the wet zone. In Maha, the harvesting phase temperature was higher, while the growing phase temperature was higher in Yala. On the whole, Yala was warmer than Maha, and the dry zone was warmer than the two other zones. The absolute difference in temperature from the previous year was between 0.39 and 0.98 °C. This being the average over time indicates the fluctuation in temperature. Thus, temperature fluctuated the most in the harvesting phase of the Maha season in the intermediate zone and the least in the growing phase of the Maha season in the wet zone. It was confirmed that rainfall was the highest in the wet zone and higher in the growing phase than in the harvesting phase. Maha was wetter than Yala, and the rainfall difference across the three climatic zones was much more pronounced during Yala than during Maha. The same patterns were observed for the number of wet days. The fluctuation of rainfall was the highest in the dry zone, and higher in the harvesting phase than in the growing phase.

Figure 2 displays the changes in maximum temperature in the three climatic zones over the four decades. The dry zone exhibited the highest maximum temperature, while the wet zone the lowest. The seasonal maximum temperature gap was the largest (up to 3 °C) in the dry zone, followed by the intermediate zone and the wet zone with almost no gap.

Figure 3 shows the trend of rainfall in the three climatic zones over the four decades. Rainfall in both growth phases of the Maha season followed almost the same patterns throughout the country, where the growing phase exhibited higher and the harvesting

Table 4 Descriptive statistics for the climatic variables in the Maha and Yala seasons by growth phase for the three climatic zones of Sri Lanka: the whole period (1981–2019). *Source*: Department of Meteorology (2020) and Department of Agriculture (2020)

Variable	Season	Growth phase	Dry zone ($n=1164$)		Intermediate zone ($n=426$)		Wet zone ($n=972$)	
			Mean	SD	Mean	SD	Mean	SD
Temperature (°C)	Maha	GS	30.58	0.78	28.65	3.80	28.52	4.09
		HS	31.13	1.23	29.72	4.08	29.71	4.00
	Yala	GS	33.38	1.39	30.89	3.53	29.41	3.84
		HS	33.09	1.69	30.63	3.81	28.17	4.06
Absolute change in temperature from the previous year (°C)	Maha	GS	0.47	0.37	0.65	0.58	0.39	0.34
		HS	0.68	0.54	0.98	0.79	0.72	0.57
	Yala	GS	0.57	0.48	0.61	0.58	0.54	0.61
		HS	0.59	0.51	0.69	0.57	0.45	0.38
Rainfall (mm)	Maha	GS	731	325	745	275	826	273
		HS	302	271	311	179	312	180
	Yala	GS	198	122	441	208	784	343
		HS	152	110	276	120	594	293
Number of wet days (days)	Maha	GS	38	10	44	10	44	9
		HS	16	9	21	10	20	9
	Yala	GS	13	7	30	9	45	11
		HS	11	6	22	8	43	11
CV for rainfall during each phase (%)	Maha	GS	222	62	195	41	196	39
		HS	384	133	321	117	319	107
	Yala	GS	401	120	253	56	201	44
		HS	443	139	298	68	210	50

CV coefficient of variation, *GS* growing phase, *HS* harvesting phase

phase had lower rainfall. The Yala season rainfall was the lowest in the dry zone and towards the highest in the wet zone, making the wet zone wetter throughout the year, except the Maha harvesting phase. The rainfall variability was much more pronounced in the Maha season throughout the country compared with the Yala season. However, this variation was the highest in the dry zone, followed by the intermediate and wet zones.

Table 5 presents the verification of the trends in climatic variables using the Mann Kendall test and linear regression. Both methods showed the positive trend in the Yala harvesting phase temperature in the dry and intermediate zones. In the wet zone, rising temperature was significant throughout the year, except the Maha harvesting phase. The rate of increase varies from 0.10 to 0.25 °C per decade. On the other hand, rainfall trend was generally not significant, except the rising trend in the growing phase of the Maha season in the dry zone.

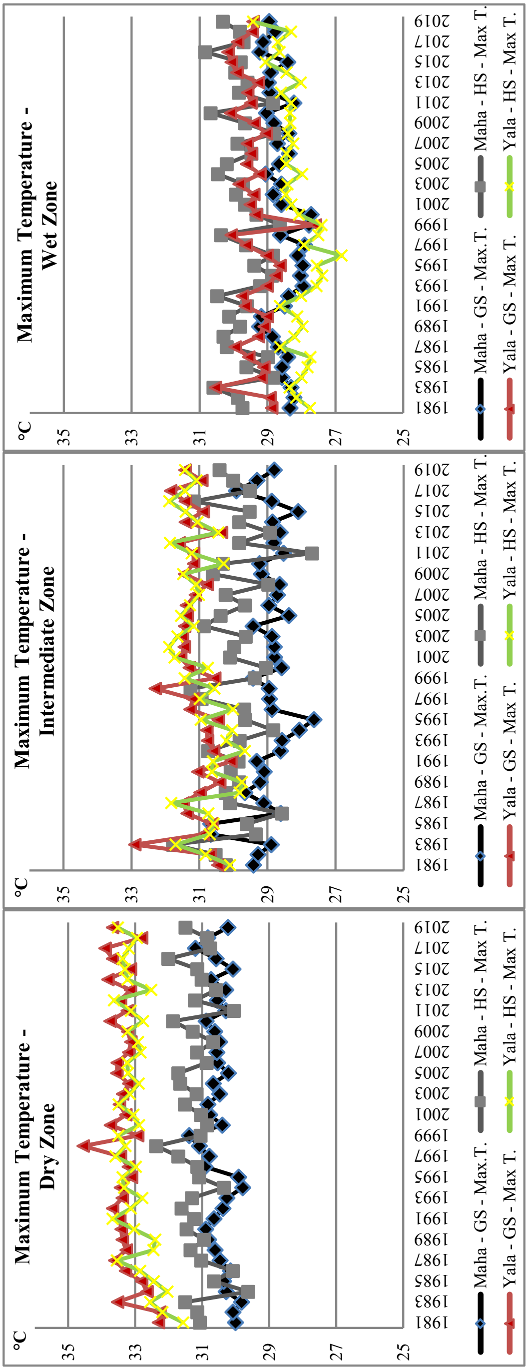

Fig. 2 Trend of maximum temperature in the dry, intermediate, and wet zones in Sri Lanka. *GS* growing phase, *HS* harvesting phase. *Source:* Department of Meteorology (2020) and Department of Agriculture (2020)

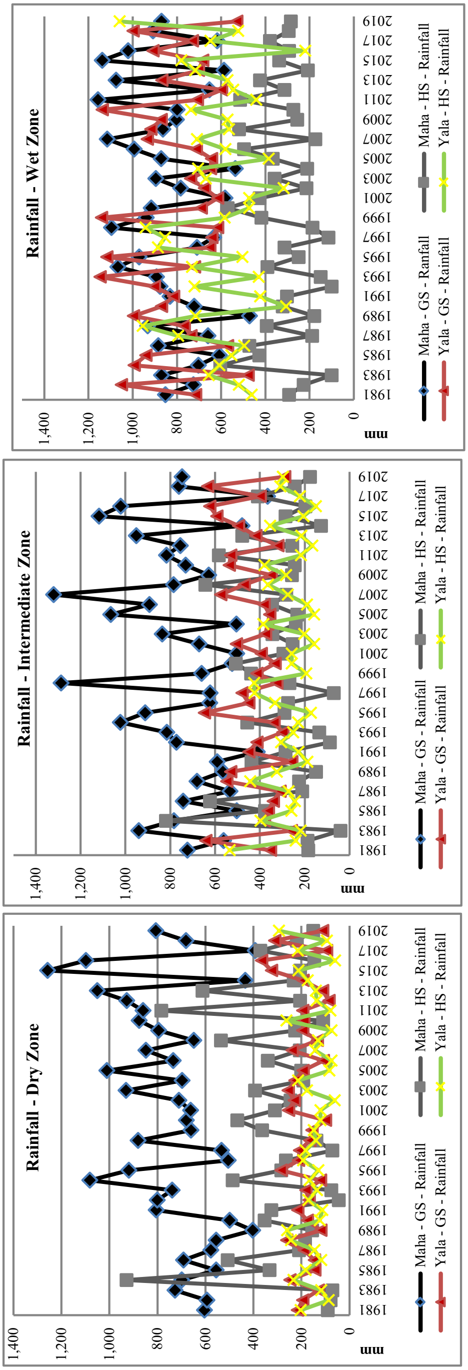

Fig. 3 Trend of rainfall in the dry, intermediate, and wet zones in Sri Lanka. *GS* growing phase, *HS* harvesting phase. *Source:* Department of Meteorology (2020) and Department of Agriculture (2020)

Table 5 Mann Kendall and linear regression of maximum temperature and rainfall in the three climatic zones of Sri Lanka

Climatic zone	Season	Growth phase	Weather parameter	Mann Kendall test and Sen's slope			Regression coefficient	
				Kendall's tau-a	*p* value	Sen's slope	Slope coefficient	*p* value
Dry zone	Maha	GS	Temperature	0.190	0.090*	0.010	0.009	0.067*
			Rainfall	0.269	0.017**	7.797	6.468	0.021**
		HS	Temperature	0.053	0.646	0.003	0.006	0.400
			Rainfall	0.066	0.562	1.202	0.792	0.779
	Yala	GS	Temperature	0.177	0.116	0.009	0.012	0.035**
			Rainfall	−0.007	0.961	−0.046	0.511	0.595
		HS	Temperature	0.277	0.014**	0.019	0.019	0.002***
			Rainfall	−0.046	0.690	−0.410	−0.298	0.728
Intermediate zone	Maha	GS	Temperature	−0.170	0.131	−0.119	−0.014	0.092*
			Rainfall	0.139	0.217	4.525	3.741	0.247
		HS	Temperature	−0.045	0.699	0.006	−0.007	0.506
			Rainfall	0.036	0.753	0.830	0.048	0.984
	Yala	GS	Temperature	0.212	0.059*	0.014	0.009	0.236
			Rainfall	0.182	0.105	2.905	2.436	0.127
		HS	Temperature	0.304	0.007***	0.025	0.025	0.004***
			Rainfall	−0.138	0.222	−1.528	−1.997	0.127
Wet zone	Maha	GS	Temperature	0.265	0.018**	0.015	0.013	0.027**
			Rainfall	0.150	0.183	3.739	3.635	0.151
		HS	Temperature	0.088	0.439	0.056	0.006	0.449
			Rainfall	0.072	0.529	1.516	1.169	0.533
	Yala	GS	Temperature	0.242	0.031**	0.015	0.012	0.095*
			Rainfall	−0.074	0.514	−1.298	−1.576	0.547
		HS	Temperature	0.363	0.001***	0.020	0.022	0.001***
			Rainfall	0.039	0.744	0.838	0.589	0.827

GS growing phase, *HS* harvesting phase

***, **, and * indicate the statistical significance at the 1%, 5%, 10% levels, respectively

4.1.2 Covariates

According to Table 6, population density was the highest in the wet zone, followed by the intermediate and the dry zone. Over time, population density increased substantially in all the zones and especially in the dry zone with a 56% growth rate.

Table 7 presents periods of fertilizer subsidy availability in the dichotomous form. Intermittently, subsidies were provided for the three main fertilizer types, namely urea, triple superphosphate, and muriate of potash.

4.1.3 Paddy yields

Table 8 presents the descriptive statistics for paddy yields for different water regimes, seasons, and the climatic zones. Yields were the highest under the major irrigation, followed by the minor irrigation and rainfed water regimes. Under the major irrigation, the seasonal yield gap was significant only in the intermediate zone. Under the minor irrigation, the seasonal yield gap was significant in all the zones, while under the rainfed conditions the season yield gap was significant in the dry and intermediate zones, but not in the wet zone.

Figure 4 illustrates the yield trends in three water regimes of two cultivation seasons in three climatic zones. The yields in all water regimes exhibited a rising trend in all the climatic zones, which was more steeper for the major irrigation paddy cultivation. Nonetheless, irrespective of the water regimes, the paddy yields showed abrupt ups and downs during the study period, reflecting disturbances caused by the external factors.

Kernel density plots (Figures S1–S6 in the Supplementary File) indicate that the yield largely followed normal distribution rather than log-normal distribution, supporting the use of the level of yield as the dependent variable in the following section.

4.2 Impacts of climate change on paddy yields

4.2.1 Dry zone

Table 9 presents the results of the panel regression analysis for the three water regimes and two growth phases in the dry zone. According to the Hausman test diagnosis, the FE model was used for both phases under the minor irrigation regime, the harvesting phase under the major irrigation, and the growing phase under the rainfed conditions, while the RE model was used for the growing phase under the major irrigation and the harvesting phase under the rainfed regime. The estimated coefficients of the quadratic terms of the harvesting phase temperature indicate nonlinear effects on paddy yields in irrigated production systems. Equation (3) and the two coefficients imply that yields would be maximized when temperature was 34.3 and 34.7 °C under the major and minor irrigation, respectively.

Table 6 Population density and its change in the three climatic zones of Sri Lanka. *Source*: Department of Census and Statistics (2021b)

Zone	1981–1983 (persons/km^2)	2017–2019 (persons/km^2)	Population density growth rate (%)	1981–2019 (persons/km^2)
Dry zone	110	171	56	143
Intermediate zone	166	234	41	200
Wet zone	543	742	37	652
Total	225	321	42	276

Table 7 Seasons/years in which the nation-wide fertilizer subsidy was available and unavailable. *Sources*: Weerahewa et al. (2010)

Available	Unavailable
1981–1989, 1995–1996, 2006–2015/2016 Maha season	1990–1994, 1997–2005
2018 Yala season–2019	2016 Yala season–2017/2018 Maha season

The absolute change in the harvesting phase temperature from the previous year showed mixed effects on the following yields: positive under the minor irrigation and negative under the rainfed conditions. Holding other variables constant, a change in temperature from the previous year in either direction by 1 °C would increase paddy yields by 143 kg/ha under the minor irrigation and decrease yields by 198 kg/ha in the rainfed areas, indicating that paddy yields in the rainfed areas tend to be more sensitive to short-run fluctuations in temperature.

Albeit with weak significance, rainfall and its variation during the growing phase negatively influenced paddy yields under the major irrigation regime. A 100-mm increase in the growing phase rainfall would reduce yields by 76 kg/ha on average, whilst a 10%-point increase in rainfall variation would reduce yields by 9.4 kg/ha. Likewise, the harvesting phase rainfall negatively influenced paddy yields in the two irrigated water regimes. With major irrigation, a 100-mm increase in the harvesting phase rainfall would reduce paddy yields by 61 kg/ha on average. There is a 95% probability that the reduction exceeds 25 kg/ha and a 5% probability that it exceeds 96 kg/ha (Table S2). With minor irrigation, a 100-mm increase in the harvesting phase rainfall would reduce paddy yields by 42 kg/ha on average. It is 95% likely that the reduction exceeds 39 kg/ha and 5% likely that it exceeds 79 kg/ha (Table S4).

Population density had a negative effect on paddy yields in the rainfed areas. An increase in population density by 100 persons/km^2 is linked to a decrease in paddy yields by 197 kg/ha in the harvesting phase equation. The fertilizer subsidy scheme had a positive effect on paddy yields under the major irrigation according to the growing phase equation. On average, the availability of fertilizer subsidy would increase paddy yields by 393 kg/ha holding all other variables unchanged. As for the two seasons in Sri Lanka, the Maha season had higher paddy yields than in the Yala

Table 8 Descriptive statistics for paddy yields (kg/ha) in the Maha and Yala seasons under the three water regimes in the following three climatic zones of Sri Lanka: the whole period (1981–2019). *Source*: Department of Census and Statistics (2021a)

Water regime	Season	Dry zone			Intermediate zone			Wet zone		
		Mean	SD	*p* value	Mean	SD	*p* value	Mean	SD	*p* value
Major	Maha	4128	930		4347	770		3734	892	
	Yala	4095	764		4081	702		3717	835	
	Average	4112	851	0.513	4211	752	0.000***	3611	886	0.783
Minor	Maha	3539	889		3805	516		3146	620	
	Yala	3630	781		3395	500		3040	650	
	Average	3586	838	0.065*	3601	547	0.000***	2919	624	0.010**
Rainfed	Maha	3185	744		3273	511		2905	538	
	Yala	3373	707		3108	547		2861	554	
	Average	3255	737	0.000***	3190	536	0.001***	2824	523	0.216

***, **, and * indicate the statistical significance at the 1%, 5%, and 10% levels, respectively

season in irrigated systems. The average seasonal difference was larger under the major irrigation than under the minor irrigation.

4.2.2 Intermediate zone

Similarly, Table 10 presents the panel regression results for the intermediate zone. The Hausman test pointed to the use of the RE model across the board. It is worth noting that unlike in the dry zone, the effects of climatic factors on paddy yields were salient only in the minor irrigation and the rainfed regimes, and not under the major irrigation. The growing phase temperature exhibited non-linear effects on paddy yields in the rainfed areas. Equation (3) and the two coefficients imply that yields would be maximized when the temperature was 26.8 °C. The absolute change in growing phase temperature from the previous year had a negative effect on paddy yields under the minor irrigation. For a 1 °C change from the previous year in either direction, paddy yields would decrease by 77 kg/ha, holding other variables constant. Besides, the harvesting phase temperature showed a negative effect on paddy yields in the minor irrigation regime. A rise in temperature by 1 °C would reduce paddy yields by 294 kg/ha.

Higher rainfall in either phase led to higher paddy yields in the minor irrigation and the rainfed areas. Specifically, an increase in the growing phase rainfall by 100 mm would raise paddy yields by approximately 24 kg/ha in both water regimes (95 to 5% percentile: 16 to 33 kg/ha under minor irrigation; 10 to 38 kg/ha under rainfed) (Tables S9 and S11), while the same increase in the harvesting phase rainfall would raise paddy yields by 55 kg/ha (23 to 87 kg/ha) under minor irrigation (Table S10) and 85 kg/ha (50 to 121 kg/ha) under rainfed environments (Table S12), holding other variables unchanged. Unexpectedly, fluctuation in the growing phase rainfall benefited paddy yields. An increase in coefficient of variation (CV) by 10% points would raise yields by 13 and 25 kg/ha in the minor irrigation and the rainfed

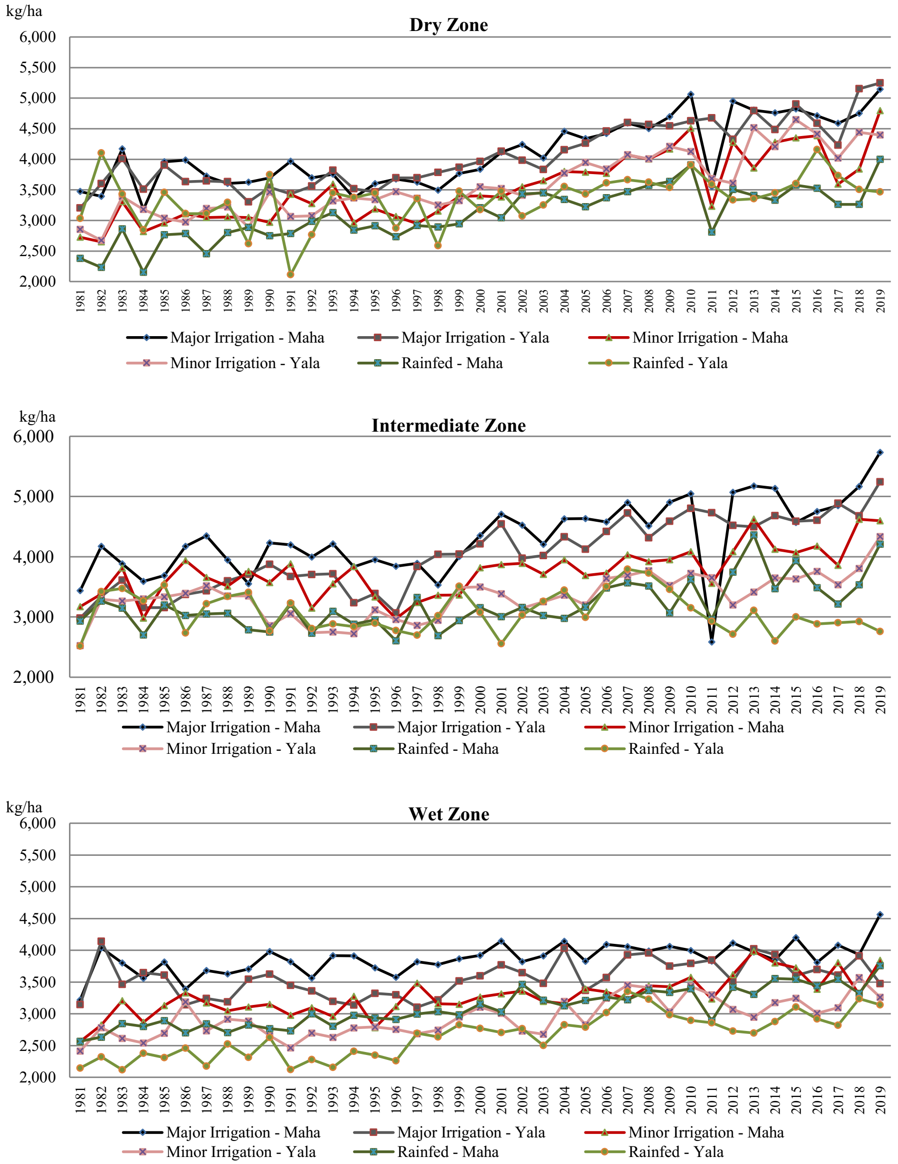

Fig. 4 Yield trend for the three water regimes, two seasons, and three climatic zones of Sri Lanka. *Source*: Department of Census and Statistics (2021a)

regimes, respectively. Conversely, fluctuation in the harvesting phase rainfall under the minor irrigation undermined yields slightly, whereby an increase in CV by 10% points would reduce yields by 4 kg/ha. On the other hand, the number of wet days during the harvesting phase negatively affected paddy yields. A 1-day increase in

Table 9 Effects of climatic variables on paddy yields in the dry zone of Sri Lanka (1981–2019): district-level panel regressions

Variable	Major irrigation		Minor irrigation		Rainfed	
	Growing phase	Harvesting phase	Growing phase	Harvesting phase	Growing phase	Harvesting phase
Growing phase temperature (°C)	1653.612 (1524.575)		1342.999 (996.174)		761.044 (1536.289)	
Growing phase temperature (°C)^2	−23.293 (22.441)		−19.007 (14.963)		−10.127 (23.852)	
Growing phase absolute change in temperature from previous year (°C)	4.257 (69.985)		−34.277 (58.636)		−56.442 (68.781)	
Growing phase rainfall (mm)	−0.760* (0.463)		−0.199 (0.154)		−0.040 (0.192)	
Growing phase CV of rainfall (%)	−0.940* (0.486)		0.427 (0.265)		0.046 (0.347)	
Harvesting phase temperature (°C)		1627.841** (533.754)		1468.733** (555.252)		1821.052 (1323.804)
Harvesting phase temperature (°C)^2		−23.724** (8.472)		−21.174** (8.663)		−26.413 (20.465)
Harvesting phase absolute change in temperature from previous year (°C)		54.449 (46.889)		143.122** (54.268)		−197.838*** (52.546)
Harvesting phase rainfall (mm)		−0.606** (0.186)		−0.416* (0.199)		−0.269 (0.215)
Harvesting phase number of wet days (days)		0.284 (7.963)		−1.790 (4.635)		7.467 (7.442)
Harvesting phase CV of rainfall (%)		−0.376 (0.287)		−0.326 (0.286)		0.064 (0.424)

Table 9 (continued)

Variable	Major irrigation		Minor irrigation		Rainfed	
	Growing phase	Harvesting phase	Growing phase	Harvesting phase	Growing phase	Harvesting phase
Population density (persons/km^2)	−0.434 (2.971)	−2.782 (4.809)	−4.662 (3.644)	−4.697 (3.307)	−0.692 (1.671)	−1.971*** (0.237)
Fertilizer subsidy (1 if available, 0 otherwise)	393.015*** (138.273)	134.813 (149.742)	432.182 (237.213)	148.373 (210.548)	−133.700 (212.634)	−255.030 (206.165)
Season dummy (1 if Maha, 0 if Yala)	695.353*** (251.364)	265.509* (124.447)	420.347*** (79.882)	131.682** (48.317)	60.113 (185.895)	13.117 (97.252)
Constant	−25,815.62 (25,728.65)	−24,115.20 (8360.91)	−20,871.16 (16,007.64)	−22,080.55** (8344.16)	−11,283.46 (24,356.53)	−28,241.18 (21,250.78)
Model	RE	FE	FE	FE	FE	RE
Wald χ^2 (p value)	420.10 (0.000)					320.69 (0.000)
F-Stat (p value)		16.54 (0.000)	11.40 (0.000)	12.43 (0.000)	4.41 (0.000)	
Overall R^2	0.440	0.425	0.384	0.415	0.384	0.426
Num. of obs.	582	582	581	581	480	480
Hausman test p value	1.000	*na*	*na*	*na*	*na*	1.000

The dependent variable is paddy yield (kg/ha)

The cluster robust standard errors are in the parentheses

CV coefficient of variation, *RE* random effect, *FE* fixed effect

***, **, and * indicate the statistical significance at the 1%, 5%, and 10% levels, respectively

frequency of wet days during the harvesting phase would reduce yields by 16 and 26 kg/ha in the minor irrigation and the rainfed areas, respectively.

Population density showed mixed results. Under the minor irrigation, an increase by 100 persons/km^2 would reduce yields by 139 and 78 kg/ha according to the growing phase equation and the harvesting phase equation, respectively, while in the rainfed areas an increase by 100 persons/km^2 would increase yields by 52 kg/ha based on the harvesting phase equation. Fertilizer subsidy had no significant effect. Last, paddy yields were significantly higher in the Maha season than in the Yala season in irrigated regimes, but did not differ in the rainfed areas. On average, the Maha season yields would be higher by 257 to 340 kg/ha than in the Yala season.

4.2.3 Wet zone

Table 11 presents the panel regression results for the wet zone. The Hausman test diagnosis allowed the use of the RE model with the harvesting phase equation for irrigated regimes and the growing phase equation for the rainfed areas; otherwise, the FE model was used. In the wet zone, only climatic factors during the growing phase in the rainfed areas exhibited high statistical significance in their effects on paddy yields. The absolute change in the growing phase temperature from the previous year had positive effects on yields. Ceteris paribus, for a 1 °C change in either direction, yields would increase by 105 kg/ha on average. In the wet zone, the growing phase rainfall showed negative effects on paddy yields in the rainfed areas. A 100-mm increase in rainfall would reduce yields by 23 kg/ha on average with the 90% confidence interval of 1.5 to 44 kg/ha (Table S17). Likewise, variability in rainfall had negative effects; an increase in CV by 10% points would decrease yields by 11 kg/ha (5 to 18 kg/ha).

In the wet zone, population density did not show consistent patterns between the growing phase equation and the harvesting phase equation, which suggests indefinite effects. Fertilizer subsidy had positive effects in the minor irrigation and the rainfed water regimes; on average, the availability of fertilizer subsidy would increase yields by 165 and 328 kg/ha, respectively. Last, paddy yields were generally higher in the Maha season than in the Yala season.

5 Discussion

In the dry climatic zone, the optimum temperature during the harvesting phase in irrigated environments was estimated to be 34–35 °C. Given that the average temperature was around 30–33 °C in the dry zone in recent years, the result implies that on average, temperature effects are positive and rising temperature does not necessarily cause yield losses; rather, lower-than-normal temperature can harm paddy yields. Positive effects of temperature on paddy productivity have been reported by several studies (Punyawardena 2007; Ghadirnezhad and Fallah 2014; Matiu et al. 2017; Nishad et al. 2018). The quadratic effects of temperature on paddy yields were in line with Ghadirnezhad and Fallah (2014) and Nishad et al. (2018) who reported, based on experimental research, that the optimum temperature for paddy cultivation

Table 10 Effects of climate variables on paddy yields in the intermediate zone of Sri Lanka (1981–2019): district-level panel regressions

Variable	Major irrigation		Minor irrigation		Rainfed	
	Growing phase	Harvesting phase	Growing phase	Harvesting phase	Growing phase	Harvesting phase
Growing phase temperature (°C)	264.406 (250.664)		−36.413 (76.102)		364.626** (165.390)	
Growing phase temperature (°C)^2	−4.788 (4.313)		−0.453 (1.332)		−6.806** (2.890)	
Growing phase absolute change in temperature from previous year (°C)	−87.397 (108.950)		−77.234*** (18.862)		−95.473 (65.897)	
Growing phase rainfall (mm)	0.148 (0.197)		0.244*** (0.054)		0.235*** (0.085)	
Growing phase CV of rainfall (%)	1.211 (0.983)		1.300** (0.475)		2.459*** (0.406)	
Harvesting phase temperature (°C)		28.882 (140.758)		−294.259* (153.514)		−147.747 (213.003)
Harvesting phase temperature (°C)^2		−0.565 (2.296)		4.146 (2.674)		2.211 (3.794)
Harvesting phase absolute change in temperature from previous year (°C)		−57.349 (74.460)		−41.592 (66.704)		6.201 (63.859)
Harvesting phase rainfall (mm)		−0.296 (0.949)		0.547*** (0.193)		0.853*** (0.214)
Harvesting phase number of wet days (days)		−1.028 (7.906)		−16.139*** (0.492)		−26.258*** (8.063)
Harvesting phase CV of rainfall (%)		0.576 (0.568)		−0.385*** (0.139)		−0.808 (1.091)
Population density (persons/km^2)	0.055 (0.607)	0.377 (0.392)	−1.386*** (0.233)	−0.779*** (0.207)	−0.303 (0.258)	0.519** (0.263)
Fertilizer subsidy (1 if available, 0 otherwise)	−98.481 (258.552)	−134.358 (218.019)	−145.242 (361.168)	−142.055 (395.793)	139.081 (477.010)	43.663 (467.787)
Season dummy (1 if Maha, 0 if Yala)	256.605** (103.234)	272.636*** (99.895)	275.177*** (43.495)	340.487*** (54.855)	169.131 (166.181)	102.875 (193.286)
Constant	−648.52 (3604.55)	2786.12 (2332.70)	4242.97*** (1410.08)	8279.80*** (2503.47)	−2767.83 (2892.22)	5424.36 (3769.42)

Table 10 (continued)

Variable	Major irrigation		Minor irrigation		Rainfed	
	Growing phase	Harvesting phase	Growing phase	Harvesting phase	Growing phase	Harvesting phase
Model	RE	RE	RE	RE	RE	RE
Wald χ^2 (p value)	237.06 (0.000)	235.54 (0.000)	269.01 (0.000)	256.64 (0.000)	79.52 (0.002)	71.59 (0.019)
F-Stat (p value)						
Overall R^2	0.588	0.588	0.618	0.609	0.324	0.304
Num. of obs.	213	213	213	213	213	213
Hausman test p value	1.000	1.000	1.000	1.000	1.000	1.000

The dependent variable is paddy yield (kg/ha)

The cluster robust standard errors are in the parentheses

CV coefficient of variation, *RE* random effect

***, **, and * indicate the statistical significance at the 1%, 5%, and 10% levels, respectively

was between 25 and 35 °C and that both extreme heat and cold during the flowering and grain filling stages led to yield reduction. Adejuwon (2006) estimated in Nigeria that paddy yields would increase if temperature increased by 2–3 °C, but would start decreasing if the increment was more than 4–5 °C. In general, extreme temperature, either high or low, causes floret abortion and pollen sterility during panicle development and the reproductive phase, which causes spikelet sterility (Punyawardena 2007; Dharmarathna et al. 2014) and grain sterility (Jagadish et al. 2007; Sridevi and Chellamuthu 2015; Gumel et al. 2017; Niang et al. 2017; Rahman et al. 2017; Walisinghe et al. 2017; Nawaz et al. 2019; Ahmad et al. 2021).

While the average temperature was lower than optimum, year-to-year fluctuation in temperature during the harvesting phase had positive effects in the minor irrigated areas and negative effects in the rainfed areas. The latter result suggests that rainfed farmers in the dry zone are unlikely to adapt promptly to a large temperature change from the previous year, be it an increase or a decrease. Flowering (anthesis and fertilization) is one of the most susceptible stages to temperature in paddy growth (Yoshida 1981; Jagadish et al. 2007). Temperature outside the optimum range induces sterility of the plant by poor anther dehiscence and low pollen production, thereby reducing germinating pollen grains (Prasad et al. 2006).

Somewhat unexpectedly, negative effects of rainfall on paddy yields were observed under irrigated regimes. It may be the case that irrigated systems in the dry zone are highly controlled production environments with the predominant dependence on irrigation water. Under such conditions, unexpected rainfall may reduce paddy yields due to transient submergence. Abeysekera et al. (2015) reported in Sri Lanka that occasional flooding during the reproductive phase in the dry zone reduced both quantity and quality of crop produce. Similar effects of high rainfall were also detected in the study of 13 agricultural states in India (Kumar and Sharma 2013) and Bangladesh (Ara et al. 2017). Furthermore, our study shows that the growing phase rainfall and its variation had larger effects than the harvesting phase rainfall. The significant rise in the growing phase rainfall of the Maha season might explain our result.

In the intermediate climatic zone, the effects of climatic factors on paddy yields were salient only in the minor irrigation and rainfed regimes, and not under the major irrigation. This tendency was also observed in the wet zone. Therefore, the importance of major irrigation observed in the dry zone seems to be wiped out in more favorable (i.e., wetter) climatic zones.

The growing phase temperature exhibited non-linear effects on paddy yields in the rainfed areas, with the estimated optimum temperature being 26.8 °C, which is lower than in the dry zone. Given the average temperature during this phase at about 30 °C, temperature practically had negative effects on paddy yields on average. Similarly, negative effects of the harvesting phase temperature were found in the minor irrigation regime. Literature tends to emphasize negative effects of temperature on the vegetative and reproductive phases of the rice plant (Yoshida 1981; Gumel et al. 2017; Rahman et al. 2017; Nawaz et al. 2019) through reduction in final leaves, leaf canopy, and photosynthetic efficiency (Yoshida 1981; Wassmann et al. 2009; Gumel et al. 2017; Nawaz et al. 2019). Some other studies delivered evidence of rising temperature reducing rainfed yields due to the heat effects on grain quality

Table 11 Effects of climate variables on paddy yields in the wet zone of Sri Lanka (1981–2019): district-level panel regressions

Variable	Major irrigation		Minor irrigation		Rainfed	
	Growing phase	Harvesting phase	Growing phase	Harvesting phase	Growing phase	Harvesting phase
Growing phase temperature (°C)	−4.048 (227.639)		−34.056 (279.655)		112.542 (157.819)	
Growing phase temperature (°C)^2	1.371 (4.004)		−0.763 (4.392)		−2.685 (3.068)	
Growing phase absolute change in temperature from previous year (°C)	52.266 (32.247)		38.474 (38.063)		105.246** (43.409)	
Growing phase rainfall (mm)	0.083 (0.119)		0.041 (0.134)		−0.227* (0.129)	
Growing phase CV of rainfall (%)	−1.895 (1.162)		−0.427 (0.434)		−1.147*** (0.397)	
Harvesting phase temperature (°C)		−336.765 (447.245)		−247.611* (127.597)		126.891 (107.428)
Harvesting phase temperature (°C)^2		6.428 (8.282)		3.655 (2.496)		−2.970 (1.966)
Harvesting phase absolute change in temperature from previous year (°C)		197.473 (186.729)		−8.470 (67.874)		14.581 (14.106)
Harvesting phase rainfall (mm)		−0.163 (0.395)		−0.034 (0.182)		−0.121 (0.137)
Harvesting phase number of wet days (days)		−0.404 (9.612)		4.096 (5.694)		2.274 (4.887)
Harvesting phase CV of rainfall (%)		1.049 (0.774)		0.337 (0.346)		0.235 (0.444)
Population density (persons/km^2)	1.566 (1.933)	−0.282** (0.135)	0.568* (0.286)	−0.056* (0.032)	0.049*** (0.018)	−0.304 (0.205)
Fertilizer subsidy (1 if available, 0 otherwise)	−29.516 (132.080)	−65.514 (155.978)	283.975* (145.162)	328.394* (170.114)	164.505* (96.066)	239.173* (109.736)

Table 11 (continued)

Variable	Major irrigation		Minor irrigation		Rainfed	
	Growing phase	Harvesting phase	Growing phase	Harvesting phase	Growing phase	Harvesting phase
Season dummy (1 if Maha, 0 if Yala)	377.442*** (76.459)	57.144 (210.630)	288.387** (113.515)	457.620*** (106.967)	423.909*** (98.988)	504.679*** (83.524)
Constant	724.24 (4017.21)	7272.29 (5419.67)	3243.11 (4901.45)	5819.80*** (1705.38)	1329.22 (1856.41)	862.09 (1534.44)
Model	FE	RE	FE	RE	RE	FE
Wald χ^2 (p value)		100.84 (0.000)		343.79 (0.000)	502.33 (0.000)	
F-Stat (p value)	3.42 (0.000)		5.31 (0.000)			9.61 (0.000)
Overall R^2	0.031	0.225	0.076	0.440	0.539	0.300
Num. of obs.	396	396	486	486	477	477
Hausman test p value	*na*	0.616	*na*	0.997	0.999	*na*

The dependent variable is paddy yield (kg/ha)

The cluster robust standard errors are in the parentheses

CV coefficient of variation, *FE* fixed effect, *RE* random effect

***, **, and * indicate the statistical significance at the 1%, 5%, and 10% levels, respectively

(Abeysekera et al. 2015; Yuliawan and Handoko 2016; Adhikari et al. 2017; Kaur and Attwal 2017; Li and Troy 2018; Kumar et al. 2021a, b; Baig et al. 2022; Bhardwaj et al. 2022; He et al. 2022). Similarly, this study found that in the intermediate zone, receiving lower temperature and higher rainfall than the dry zone, temperature negatively affected yields, with greater impacts recorded in the rainfed areas.

Positive effects of rainfall during both phases were identified in the minor irrigation and rainfed regimes in the intermediate zone. Extensive literature indicates that sufficient rainfall benefits paddy yields (Kumar and Sharma 2013; Bhatt et al. 2014). Water scarcity delays flowering stage, increases spikelet sterility, reduces the number of grains per panicle, and decreases grain weight (Sarvestani et al. 2008; Pheakdey et al. 2017). In principle, many plants grow better when given sufficient rainwater throughout the growth cycle (Gumel et al. 2017; Ahmad et al. 2021). Evidence in this line was provided for paddy yields in tropical Asia, such as Bangladesh (Chowdhury and Khan 2015; Mamun et al. 2015), Nepal (Devkota and Paija 2020), India (Tsusaka and Otsuka 2013a), and Vietnam (Le 2016).

Rainfall variability exhibited somewhat puzzling effects in the intermediate zone. CV in the growing phase rainfall had positive effects on paddy yields in the minor irrigation and rainfed areas, whereas CV in the harvesting phase rainfall had negative effects. In general, literature reports that higher variance of rainfall increases yield variability, while decreasing mean yields (Bhatt et al. 2014; Matiu et al. 2017; Pheakdey et al. 2017). Similarly, in northern Togo, a rise in variability of intra-seasonal rainfall led to a reduction in paddy yields (Ali 2018).

Turning to the wet climatic zone, negative effects of rainfall were observed in the rainfed areas. In wetland rainfed environments in general, flooding is a greater concern than droughts, which might explain this result. This is consistent with some other studies on paddy production in South Asian wetland context (Kumar and Sharma 2013; Ara et al. 2016). Variability in the growing phase rainfall negatively affected rainfed paddy yields. Kumar and Sharma (2013) and He et al. (2013) underscored that unpredictable rainfall pattern was one of the leading causes of yield losses in wet production environments. Rahman et al. (2017) also found that the effects of erratic rainfall patterns were more severe in the rainfed farming than in the irrigated farming, which is consistent with our finding.

Regardless of the climatic zones, this study observed negative effects of population density, by and large, on paddy yields. Lower population density may allude to the dominance of the agriculture sector in those provinces and districts, which may be associated with higher productivity. In Sri Lanka, the Department of Census and Statistics (2021a) showed a positive relation between farm size and productivity, which is consistent with our finding, but inconsistent with literature from developing countries in general on the grounds of lower productivity of hired labor engaged in larger farms. Furthermore, mainstream literature argues that increasing land scarcity caused by population growth induces the diffusion of land-saving and yield-enhancing technologies in Asia (Tsusaka and Otsuka 2013a, b; Rahman et al. 2017).

Likewise, this study observed significant positive effects of the availability of fertilizer subsidy on paddy yields under the major irrigation in the dry zone, and the minor irrigation and rainfed cultivation in the wet zone. This result is consistent with a host of other studies (Kumar and Sharma 2013; Perera et al. 2016; Wijetunga and Saito 2017; Walisinghe et al. 2017; Ranathilaka and Arachchi 2019; Chandrasiri et al. 2020). Moreover, the magnitude of the effects was greater in the irrigated water regimes than in the rainfed conditions. Literature discussed the synergetic effects of water and nutrient uptake on paddy yields (Zhang et al. 2018; Mboyerwa et al. 2021). Uniform irrigation water contributes to reducing the spatial variability of nutrients from fertilizer and improving fertilizer use efficiency (Mikkelsen et al. 2015). Niang et al. (2017) found in Africa that in warm environments, farmers applied larger amounts of mineral fertilizer in the irrigated lowland than in the rainfed areas.

In all climatic zones, paddy yields were significantly higher on average in the Maha season than in the Yala season, which may be due to the difference in water availability (Punyawardena 2007; Walisinghe et al. 2017; Wijetunga and Saito 2017; Esham et al. 2018; Abeywardana et al. 2019; Ranathilaka and Arachchi 2019; Chandrasiri et al. 2020).

6 Conclusion

While abundant literature has assessed climate change impacts on agricultural production globally, limited literature has investigated the impacts of climatic factors on paddy yields under different water regimes in various climatic zones of Sri Lanka. This study estimated the impacts of temperature, rainfall, and their variability on paddy yields for the dry, intermediate, and wet climatic zones and for the major irrigation, minor irrigation, and rainfed water regimes by drawing on the district-level panel dataset covering 18 districts for 39 years. The panel regression analysis revealed both positive and negative effects of various climatic variables included in the estimation models. It was found that the effect of rising temperature on rice productivity was positive in the dry zone and negative in the intermediate zone, due to the different optimum levels of temperature between the two zones, as identified by this study. Temperature variability showed mixed effects on paddy yields, depending on the water regime and the climatic zone. Both quantity and variability of rainfall showed mixed results regarding their effects on paddy yields, depending on the climatic zone and the water supply regime. Yet, there was an indication from the intermediate and wet zones that rainfall may be more or less sufficient in the major irrigation regime yet suboptimum in the less irrigated regimes.

The findings imply that paddy production in Sri Lanka has been threatened by climate change and variability, especially variability in temperature during both the growing phase and the harvesting phase of paddy growth. Hence, adaptive capacity to temperature fluctuation should be enhanced, which would help increase and stabilize paddy productivity in rainfed environments of the dry zone. Therefore, it is essential to strengthen information management systems to provide timely weather forecast and information on improved agronomic practices. Weather-based crop insurance schemes for paddy farming may also contribute to protecting smallholder farmers in times of weather shocks. Furthermore, as rainfed paddy production systems were noted as more vulnerable than irrigated production systems, with mixed effects in different climatic zones, it is recommended that the government reinforce its support for installing and upgrading irrigation facilities across the climatic zones to minimize climate-induced crop failure in the rainfed areas. In all likelihood, strategies for climate-smart agriculture should incorporate the characteristics of each climatic zone and each water regime to formulate location-specific policies rather than general policy applications across the nation.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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