



Modeling the Influence of Seasonal Climate Variability on Soybean Yield in a Temperate Environment: South Korea as a Case Study

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Abstract

Korea's agriculture system has been significantly influenced by climate change over the years. The uncertainties of climate change and variability are important considerations to respond to increasing food demand around the world. There is limited information on the impact of climate variability on soybean yield in temperate regions generally, and Korea in particular. This study, therefore, sought to identify the impact of seasonal climate variability on soybean yield in Korea. Specifically, the study analyzed soybean yield characteristics in Korea's temperate climate using statistical techniques, evaluated climate features over the study period (1979–2016) using the Mann–Kendall test and Sen's slope analysis, analyzed the relationship between yield and climatic variables through correlation analysis, and built a statistical model using significant climatic variables. Results showed that climate variability significantly influenced soybean yield in Korea with an R^2 value of 0.455 and significant at $P \leq 0.05$, implying that the climatic variables accounted for 45.5% of the variation in soybean yield. The results confirm the significant role played by climate on the yield of soybean in Korea, thus assisting in the development of adequate adaptation and mitigation strategies by farmers and policy makers alike, based on this credible knowledge. In addition, the soybean crop has increasingly become an important crop in Korea over the years, hence research as this, geared towards improvement of soybean production in the face of changing climate is of utmost priority as we aim to sustain and improve food security.

Keywords Climate change · Food security · Seasonal variability · Soybean yield · Korea

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Introduction

According to the World Bank database, agriculture contributes about 1.8% of the gross domestic product of South Korea (World-Bank 2021). This is owing to the fact that 70% of the country's land is mountainous and generally unsuitable for large-scale commercial farming (USDA 2018). Despite these shortcomings, South Korea remains a major producer of agricultural crops such as rice, cabbage, onion, potato, apple, tomato, persimmon, soybean, strawberry, amongst others, in the world (FAO 2018), owing to its rapid advancement in agro-related technology (Huang and Brown 2019). Numerous scientific investigations have been inspired by multi-sectoral impact assessment and mitigation of climate change in the recent past, and this trend will continue in the future (Ahmad et al. 2019; Lindner et al. 2015; Odey et al. 2021b). This is so because during the last 100 years, climate change has been observed all over the world, and it has had a substantial impact on crop productivity (Azad et al. 2018; Doğan et al. 2019; Stocker 2014). The earth's

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average temperature has risen by 1.5 °C per year, coupled with erratic rainfall patterns, reduced winter seasons, and lengthened summer seasons (Lee et al. 2012). This has resulted in progressive instability in agricultural production and an increase in the damages caused by harmful insects and blights (Rong et al. 2020).

In South Korea, increases in carbon dioxide (CO₂) density (Adelodun et al. 2021b), the booming population in surrounding Asian countries like China and India, and urbanization (Adelodun et al. 2021a) have resulted in a yearly average temperature increase of 1.5 °C over the last 100 years (Kim et al. 2018; Lee et al. 2013) as shown by historical meteorological observations. The urbanization effect accounts for 20–30% of the total (Chang-Gil 2008). Temperature, rainfall and relative humidity have all had an impact on agricultural crop yield maximization in temperate climes (due to climate change). Temperature rises enhance crop productivity in the highlands while having negative consequences in the lowlands due to increased water scarcity (Poudel and Shaw 2016). Rainfall variation causes water stress that reduces leaf area as stomata closes to reduce water loss and promote pollen sterility, resulting in poor quality yields (Barnabás et al. 2008). Relative humidity regulates crop transpiration and water balance, and sub-optimal levels can limit crop yield and reduce quality of produce (Ferrante and Mariani 2018). Heat stress is often times coupled with water stress, which causes dehydration of plant tissues and overheating, and the combined impacts are far more damaging to the crop than the individual occurrences (Porter and Semenov 2005).

Soybean as a predominantly rain-fed crop is influenced by these climatic factors (Herrero et al. 2010; Mulungu et al. 2021), hence the quantification of the relationship between climatic factors and crop yield remains a challenge (Arefinia et al. 2021). Plant growth in an agricultural system depends on the integrated response of various eco-physiological processes. Since it is virtually impossible to accurately account for the interaction between these processes for determining their potential effects on crop yield, development of effective models remain a viable option (Aparecido et al. 2021; Kim et al. 2013). Many studies exist that have analyzed the influence of climatic factors on crop yield through modeling approaches. However, most of these studies were conducted using crop simulation models and small variations in climatic factors, particularly temperature, are often omitted (Schlenker and Roberts 2008). Hence, regression models based on historical yield and climate data are reasonably reliable in predicting yield changes due to climate change (Lobell and Field 2007; Lobell et al. 2005; Poudel and Shaw 2016). Few studies have been conducted on the impact of climate change/variability on crop yield in the temperate regions. In South Korea particularly, majority of these studies focus on rice (Kim et al. 2013; Kim and Pang 2009; Lee et al. 2012; Nasrullah et al. 2021; Park et al. 2018; Yoon

et al. 2019), with scarce information available on soybean. Furthermore, available studies often target specific agro-meteorological stations/locations (Yoon et al. 2021) and they demonstrate a limited ability to describe the effects of climate variables on national yield. Since soybean growth is highly susceptible to climate conditions, it is vital to understand the effects of changing climate in South Korea on yield in order to maintain long-term soybean production and availability. The existence of this significant knowledge gap serves as the foundation for this study. The objectives were, therefore, to analyze soybean yield characteristics in South Korea's temperate climate, evaluate the climate features over the study period, explore the relationship between regional climatic variables and soybean yield, and build a statistical model to show the impact of climate variability on soybean yield based on the significant climate regions. In addition, the credibility of the model was evaluated using the Taylor diagram. This study makes the assumptions that factors affecting soybean yields, such as insect and disease infestation, and poor farming techniques, are not present; climate variability causes soybean yield fluctuation, and not vice versa; and finally, climate variables are not the cause of errors in soybean yield data (Mumo et al. 2018).

Data and Methodology

Study Area

South Korea is situated between latitudes 33° and 39° N, and longitudes 124° and 130° E, with elevations between 0 and 1950 m above sea level (Fig. 1). The country occupies the southern part of the Korean peninsula, with a total area of 100,032 km² that is predominantly mountainous, and a population of about 51.71 million people (Odey et al. 2021a). It is divided into nine (9) provinces for administrative purposes, including Gyeonggi, Gangwon, North Chungcheong, South Chungcheong, North Gyeongsang, South Gyeongsang, North Jeolla, South Jeolla, and Jeju. In Gyeonggi, the average annual temperature is 11.7 °C. The coldest month is January, with an average of -2.8 °C, and the hottest month is August, with 25.1 °C. The average annual precipitation is 1267.9 mm. January has the lowest precipitation at 16.9 mm, and July has the highest at 354.9 mm. The average annual wind speed is 2.1 m/s, and the average annual relative humidity is 68.0%. In Gangwon, the average annual temperature is 10.8 °C. The coldest month is January, with an average of -8.7 °C, and the hottest month is August, with 28.2 °C. The average annual precipitation is 1377.1 mm. The lowest precipitation lies between December and January at 24.6 mm, and the highest between July and August at 346.9 mm. The average annual wind speed is 1.9 m/s, and the average annual

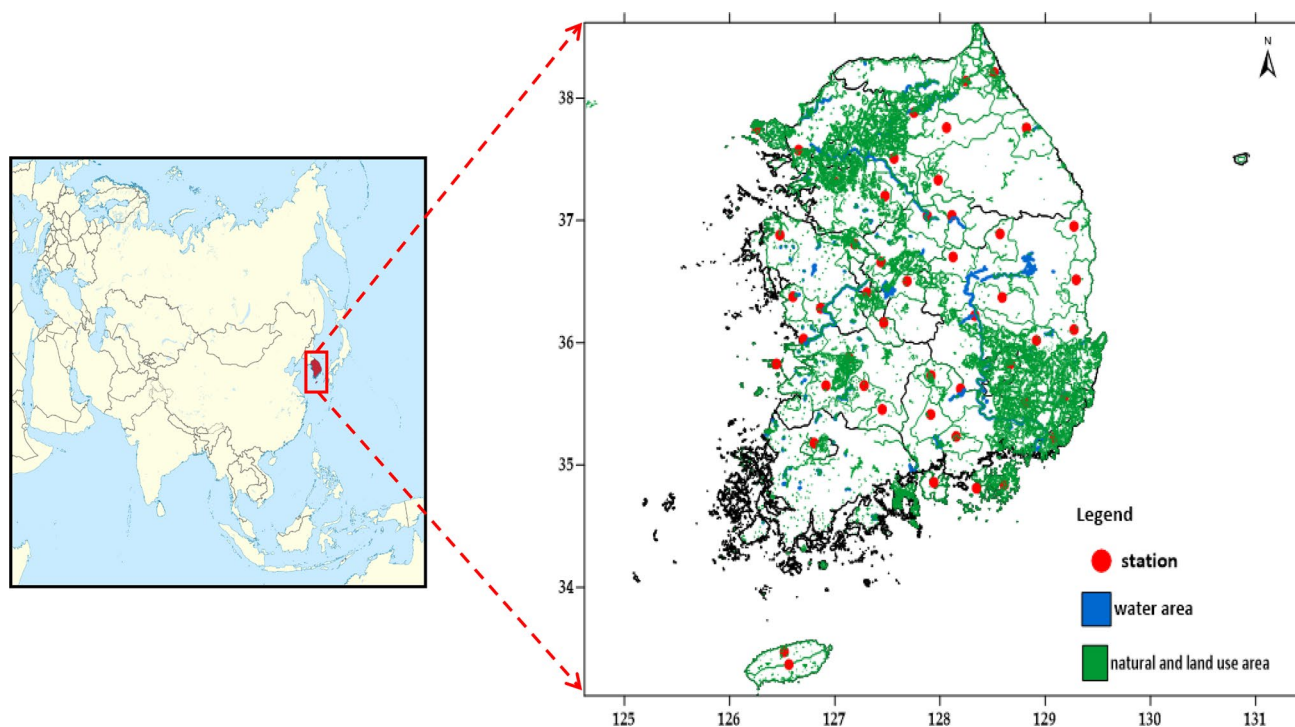


Fig. 1 Location map of South Korea, in Asia; inset shows South Korea's water area, natural and land use area, and the synoptic stations employed in this study

relative humidity is 67.0%. In North Chungcheon, the average annual temperature is 11.6 °C. The coldest month is January, with an average of -2.8 °C, and the hottest month is August, with 24.7 °C. The average annual precipitation is 1261.3 mm. The highest precipitation occurs during the summer (June to August) at an average of 726.7 mm, and the lowest during the winter (December to February) at an average of 77.9 mm, making up 57.5% and 6.2% of the annual precipitation respectively. The average annual wind speed is 1.7 m/s, and the average annual relative humidity is 67.0%. In South Chungcheon, the average annual temperature is 12.4 °C. The coldest month is January, with an average of -1.3°C, and the hottest month is August, with 25.6 °C. The average annual precipitation is 1271.7 mm. The highest precipitation (55–60%) occurs during the summer and the lowest (5–10%) during the winter. The average annual wind speed is 1.7 m/s, and the average annual relative humidity is 71.0%. In North Gyeongsang, the average annual temperature is 12.6 °C. The coldest period lies between December and January, with an average of 2.1 °C, and the hottest month is August, with 29.9 °C. The average annual precipitation is 1091.7 mm. The lowest precipitation occurs in the winter at 80.0 mm, and the highest in the summer at 574.3 mm. The average annual wind speed is 2.2 m/s, and the average annual relative humidity is 66.0%. In South Gyeongsang, the average annual temperature is 13.9 °C. The coldest period lies between December and

January, with an average of 3.2 °C, and the hottest month is August, with 29.7 °C. The average annual precipitation is 1516.0 mm. The lowest precipitation occurs in the winter at 102.8 mm, and the highest in the summer at 736.2 mm. The average annual wind speed is 1.9 m/s, and the average annual relative humidity is 66.0%. In North Jeolla, the average annual temperature is 12.5 °C. The coldest month is January, with an average of -5.7°C, and the hottest month is August, with 29.7 °C. The average annual precipitation is 1326.8 mm. The highest precipitation occurs during the summer at 743.5 mm, accounting for about 56% of the annual precipitation. The average annual wind speed is 1.7 m/s, and the average annual relative humidity is 72.0%. In South Jeolla, the average annual temperature is 14.0 °C. The average annual precipitation is 1369.6 mm. The average annual wind speed is 2.9 m/s, and the average annual relative humidity is 71.0%. In Jeju, the average annual temperature is 16.1°C. The average annual precipitation is 1558.3 mm. The average annual wind speed is 3.0 m/s, and the average annual relative humidity is 72.0% (KMA 2020). Generally, the Korean climate is influenced by the Asian monsoon, with distinct monsoon winds and a mix of continental and oceanic elements. It has four distinct seasons (spring, summer, autumn, and winter), characterized by heavy rainfall and hot and humid temperatures in the summer months (June–August), and extremely cold temperatures in the winter (December–February). The

other two seasons, spring (March–May) and autumn (September–November), experience occasional rainfall. Due to the diverse variations in topography and elevation, the rainfall and temperature vary spatially and seasonally. Climate change effects have hugely affected South Korea in the past, with reports indicating a possibility of increase in crop yield fluctuations due to flood and drought stresses in the near future (Dhungana et al. 2019; Lee et al. 2018). Soybean as a significant crop is cultivated in all nine (9)

provinces of the country. For a full season cultivation (considered in this study), the soybean growing period is from May to September (Table 1) (NICS 2020).

Data Sources

This study utilized daily cumulative rainfall (mm), surface air minimum and maximum temperature (°C), and relative humidity (%) data from 60 synoptic stations distributed throughout

Table 1 Considered crop and climate data

Crop	Cultivation Period	Climate Variables	Data Available
Soybean	From May to September (Full Season)	Rainfall (mm) Minimum and Maximum Temperatures (°C) Relative Humidity (%)	1979–2016

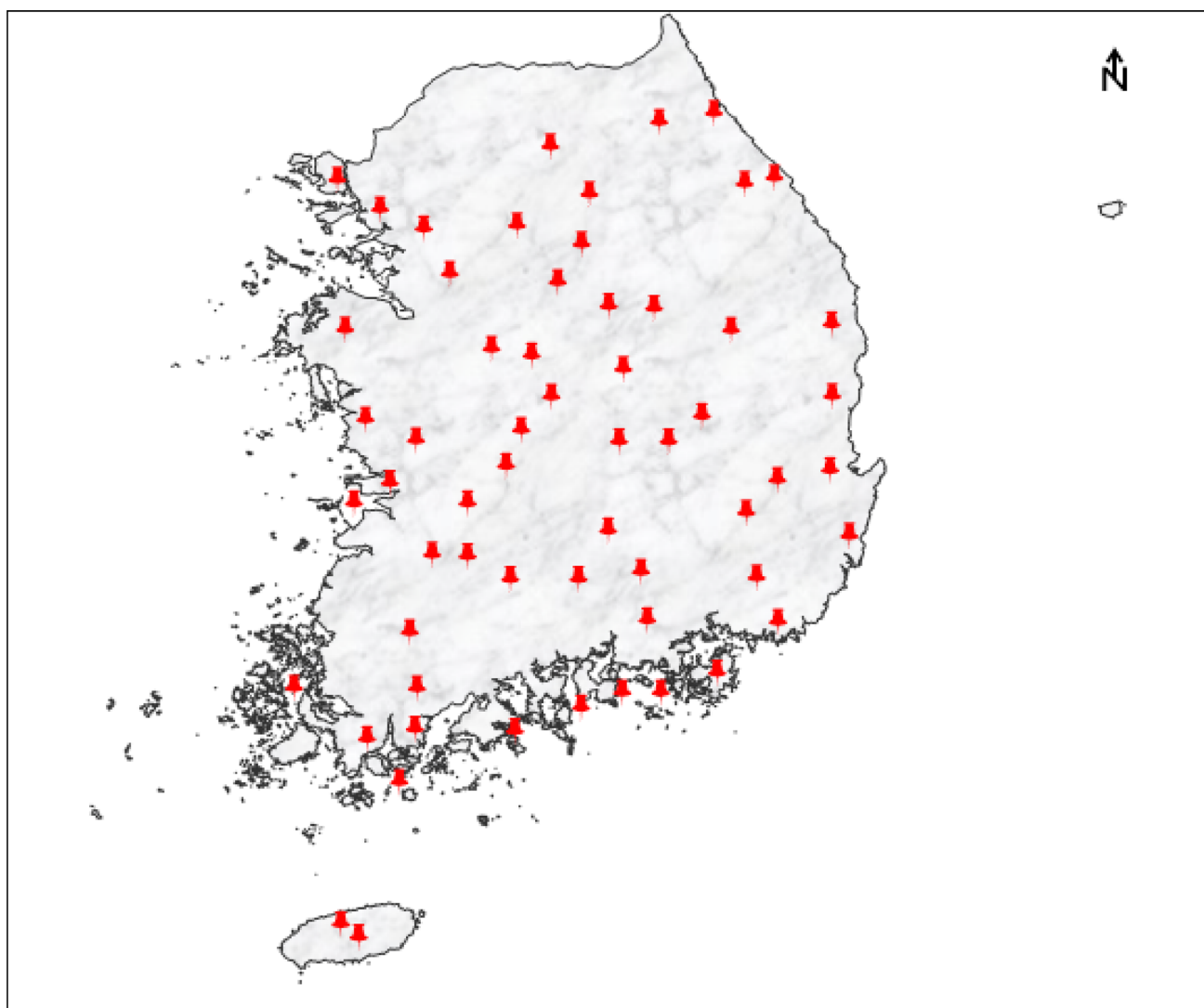


Fig. 2 Map of South Korea showing weather station distribution

the country (Fig. 2). Information on these synoptic stations is depicted in Table 2. This data was obtained from the reputable Korean Meteorological Administration (KMA 2020) for 38 years (1979–2016). World soybean yield (tons/hectare) data was obtained from the Food and Agriculture Organization (FAO 2020), and yearly national soybean yield (tons/hectare) data was acquired from the Korean Statistical Information Service (KOSIS 2020). The soybean yield data were calculated as an average of all reported soybean yields obtained from the country's cultivated area. This was computed as:

$$\text{Yield} = \frac{\text{Total production (000' tons)}}{\text{Area sown (000' ha)}} \quad (1)$$

Statistical Analyses

Descriptive Statistics

The seasonal mean precipitation, minimum and maximum temperature, and relative humidity were calculated from daily data using basic statistical techniques. Since climatic factors have no direct effect on yield during non-growing crop periods, climate indices were developed based on the weather during the growing season (Mumo et al. 2018). The assumption of a fixed growing period thus contributes to uncertainties in the regression model. In addition, a first differencing method that eliminates trend effects of land practices and technological change over time was employed to evaluate soybean variations caused by climate. According to Liang et al. (2017), this method allows regression analysis to focus on inter-annual variations while avoiding station-ary issues.

Table 2 Considered synoptic stations

No.	Station	Elevation (m)	Latitude (N) and Longitude (E)	No.	Station	Elevation (m)	Latitude (N) and Longitude (E)
1	Seoul	85.8	37.5714° N, 126.9658° E	31	Mokpo	38	34.8169° N, 126.3812° E
2	Incheon	68.2	37.4776° N, 126.6244° E	32	Yeosu	64.6	34.7393° N, 127.7406° E
3	Suwon	34.1	37.2723° N, 126.9853° E	33	Wando	35.4	34.3959° N, 126.7018° E
4	Ganghwado	46.4	37.7074° N, 126.4463° E	34	Suncheon	169.6	35.0204° N, 127.3695° E
5	Yangpyeong	47.9	37.4886° N, 127.4945° E	35	Jangheung	45.1	34.6889° N, 126.9195° E
6	Icheon	78	37.264° N, 127.4842° E	36	Haenam	13.2	34.5536° N, 126.569° E
7	Sokcho	17.5	38.2509° N, 128.5647° E	37	Goheung	53.8	34.6183° N, 127.2757° E
8	Daegwallyeong	772.6	37.6771° N, 128.7183° E	38	Uljin	50	36.9918° N, 129.4128° E
9	Chuncheon	75.6	37.9026° N, 127.7357° E	39	Chungnyeong	243.7	36.2202° N, 127.9946° E
10	Gangneung	26	37.7515° N, 128.891° E	40	Pohang	2.9	36.032° N, 129.38° E
11	Wonju	142.1	37.3376° N, 127.9465° E	41	Daegu	50	35.8782° N, 128.6522° E
12	Inje	200.2	38.0599° N, 128.1671° E	42	Yeongju	210.6	36.8718° N, 128.5169° E
13	Hongcheon	140.9	37.6836° N, 127.8804° E	43	Mungyeong	170.6	36.6273° N, 128.1488° E
14	Chungju	114.2	36.9704° N, 127.9525° E	44	Yeongdeok	40.6	36.5334° N, 129.4093° E
15	Cheongju	57.2	36.6392° N, 127.4407° E	45	Uiseong	81.8	36.3561° N, 128.6886° E
16	Jecheon	263.6	37.1593° N, 128.1943° E	46	Gumi	48.9	36.1306° N, 128.3205° E
17	Boeun	175	36.4876° N, 127.7341° E	47	Yeongcheon	93.6	35.9774° N, 128.9514° E
18	Seosan	25.9	36.7766° N, 126.4939° E	48	Ulsan	33.6	35.5601° N, 129.3203° E
19	Daejeon	68.9	36.372° N, 127.3721° E	49	Busan	69.6	35.1047° N, 129.032° E
20	Cheonan	28	36.78° N, 127.1184° E	50	Tongyeong	32.3	34.8454° N, 128.4356° E
21	Boryeong	10	36.3272° N, 126.5574° E	51	Jinju	30.2	35.1638° N, 128.04° E
22	Buyeo	11.8	36.2724° N, 126.9208° E	52	Geochang	50.8	35.3482° N, 126.599° E
23	Geumsan	170.3	36.1056° N, 127.4817° E	53	Hapcheon	32	35.565° N, 128.1699° E
24	Gunsan	23.2	36.0053° N, 126.7613° E	54	Miryang	11.2	35.4915° N, 128.7441° E
25	Jeonju	61.4	35.8408° N, 127.1172° E	55	Sancheong	138.1	35.413° N, 127.8791° E
26	Buan	12	35.7295° N, 126.7166° E	56	Geoje	45.4	34.8882° N, 128.6046° E
27	Imsil	247.1	35.6123° N, 127.2856° E	57	Namhae	43.7	34.8167° N, 127.9264° E
28	Jeongeup	44.6	35.5632° N, 126.8661° E	58	Jeju	20.4	33.5141° N, 126.5297° E
29	Namwon	132.5	35.4213° N, 127.3965° E	59	Seongsan	17.8	33.3868° N, 126.8802° E
30	Gwangju	70.4	35.1729° N, 126.8916° E	60	Seogwipo	47	33.2462° N, 126.5653° E

Mann–Kendall Test

The seasonal trends of precipitation, minimum and maximum temperature, and relative humidity were analyzed using the Mann–Kendall test (Kendall 1975; Mann 1945). This is a robust non-parametric test, used to detect the existence of positive (increasing) or negative (decreasing) trends in time-series. This method is thought to be superior to parametric tests because it is not affected by extremes, and does not rely on the magnitude of missing data. In the testing process, the hypothesis was set as; Null hypothesis (H_0), indicating no trend in the series from which the dataset was drawn. Alternate hypothesis (H_1), indicating a trend in the series. If $P \leq 0.1$, the H_0 will be rejected.

Similarly, the Sen's slope method was used to quantify the trend. Sen's slope is a non-parametric approach devised by Sen (1968), that can be used to quantify a trend. It is computed using the following equation:

$$Q_i = \frac{X_j - X_k}{j - k} \quad \text{for } \theta \ i = 1, 2, 3, \dots, N \quad (2)$$

where X_j and X_k represent data values at time j and k ($j > k$), respectively. The Sen's estimator of slope is the median of these N values of Q_i . If N is odd, the Sen's estimator is calculated as $Q_{\text{med}} = Q(N+1)/2$, and if N is even, it is calculated as $Q_{\text{med}} = [Q(N/2) + Q(N/2+1)]/2$. Finally, Q_{med} is tested using a two-sided test with a confidence interval of 100% ($1 - \alpha$), and the true slope is determined.

Changes in Climate–Crop Yield Relationship

To determine the climate–crop yield relationship, correlation coefficient and multiple linear regression analysis were performed using the Statistical Package for Social Sciences (SPSS). Regions having the most climate stress to soybean production were identified through the performance of correlation analysis between climate anomaly indices (precipitation, relative humidity, minimum and maximum temperature) at each synoptic station and the anomalies of national yield. In other words, the correlation analysis measured the strength of the association between climate variability at each station, and the national yield. The averages of specific climate index over all the regions showing significant correlation (positive or negative), formed the climate indices used in building the multiple regression model (Kucharik and Serbin 2008; Mumo et al. 2018). The regression analysis confirmed the percentage variation of the response variable from the predictor variable that is explained by a linear model. It is expressed mathematically as:

$$y(t) = \beta_0 + \beta_1 X_1(t) + \dots + \beta_n X_n(t) + \varepsilon \quad (3)$$

where $y(t)$ is the soybean yield in year t ($t = 1, 2, 3, \dots, 38$), β_0 is the y -intercept which represents unit change of the dependent variable, $X_1, X_2, \dots, X_n$ are average precipitation, relative humidity, minimum and maximum temperatures in stations having significant correlations between yield and climatic variables.

In the development of the model, the following assumptions were made: the model relationship is linear, error terms are independent, and the variance of the error term is constant for each value of the predictors (homoscedasticity). These three (3) assumptions were evaluated using scatterplots. Other assumptions made include; normal distribution of residuals (evaluated using the histogram and normal probability plot), and no multicollinearity (evaluated based on the correlation matrix and the variance inflation factor). The assumptions were made and evaluated to avoid possible complications as well as achieve the best possible selection of explanatory variables. None of the assumptions was violated thus the model was adjudged appropriate for the analysis.

Taylor Diagram

Taylor Diagrams (Taylor 2001) are a graphic illustration of how well a pattern (or group of patterns) matches observations. In other words, they explain the similarity or dissimilarity between modelled and observed results. This similarity/dissimilarity is measured in terms of their correlation, centered root-mean-square difference, and variation amplitude (represented by their standard deviations). The Taylor diagram was used in this study to understand the level of relation between the modelled and the observed soybean yield.

Results and Discussion

Soybean Yield Characteristics

Soybean quality and yield are inextricably linked to the growing phase, which is influenced by the planting season and geographical region (Li et al. 2021). Full-season cultivation of soybean in Korea is characterized by longer growth period that brings about higher seed yield. Planting is normally done between early to late May while harvesting is carried out from late September to early October. Depending on the soybean cultivar, it takes an average of 85–150 days to reach full maturity (FAO 1998). Over the study period, the average soybean yield in South Korea was 1.785 tons/ha/year. This was much less than the world soybean average, which stood at 2.131 tons/ha/year over the same period (Fig. 3a). Both South Korea and World yield showed significant increasing trends at 95% confidence level, with the

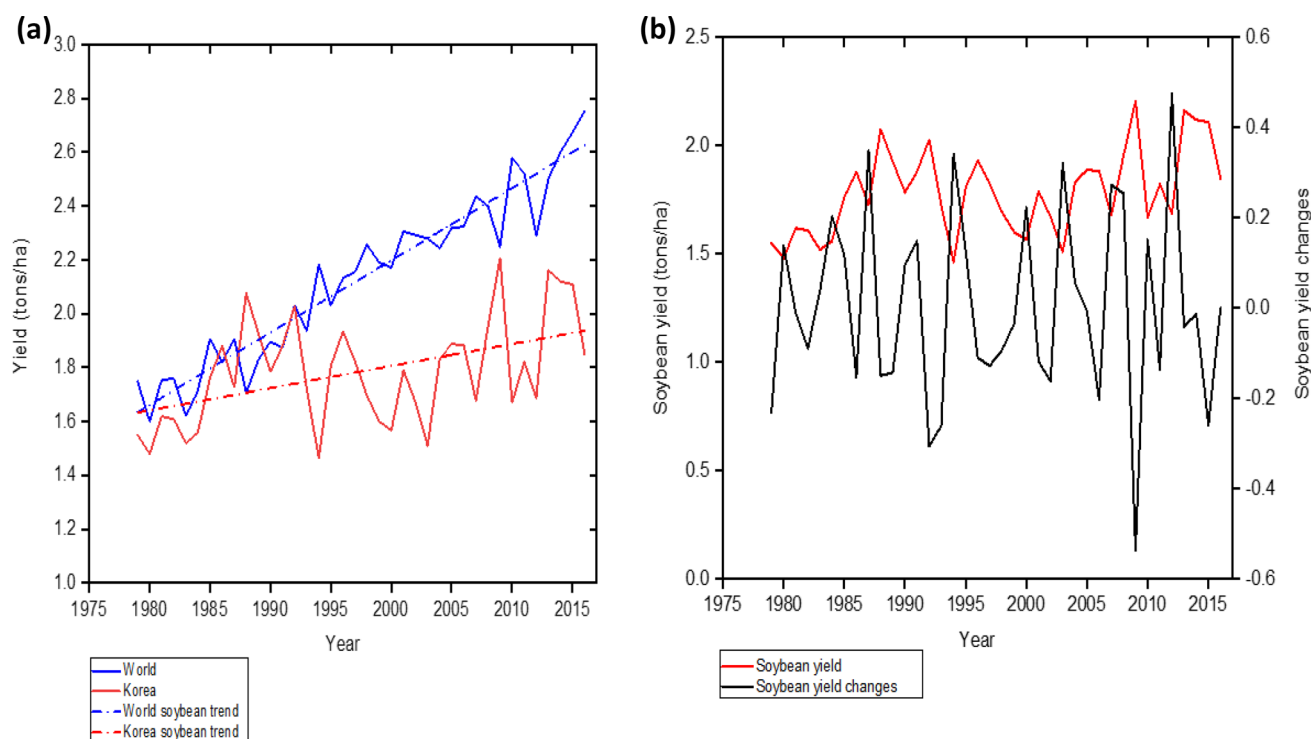


Fig. 3 **a** Temporal series of soybean production in South Korea in comparison with the world average. **b** South Korea's soybean yield (red) and yearly yield changes (black) over time (1979–2016)

former increasing at a rate of 0.008 tons/ha/year, and the later at a rate of 0.03 tons/ha/year. The increase in world production over time is due to the large planting areas in top producing countries such as the USA, Brazil, Argentina, and China; coupled with the high investment in technology and use of genetically modified seeds. In South Korea specifically, the increasing trend is associated with the rapid development in genome sequencing technology, which has improved the soybean breeding program over the years (Lee et al. 2015; Li et al. 2020).

Despite the positive trend, the national yield however, showed greater year-to-year variability over time when compared to world yield (Fig. 3b), with a standard deviation of 0.198 tons/ha. External disturbances such as climate, pests and diseases, and government policies are primarily responsible for this high variability. As observed from Fig. 3b, there were several incidences of below average yield over the study period, indicating the high sensitivity of soybean production to climate variations in the study area. Numerous diseases and insect pests have been reported to be wreaking havoc on soybean growth and seed quality in South Korea. Soybean mosaic virus (SMV) and bacterial pustule in diseases, and soybean pod borer (*Leguminibora glycinivorella*), bean bug (*Riptortus clavatus*), and aphids in insect pests, respectively, are the most problematic and destructive diseases and insect pests affecting soybean production (NICS

2020). The variability in soybean production can also be attributed to the fluctuations in production area due to the influence of urbanization and population expansion, which have been very significant over the years (KOSIS 2020).

Trend Analysis of the Climatic Variables over the Study Period

The spatial distribution of seasonal trends in climatic variables affecting soybean growth is shown in Fig. 4. It can be seen that there was no significant trend in precipitation in any of the stations (Fig. 4a), during the cropping season. On the other hand, there was a significant increasing trend in maximum and minimum temperatures for majority of the stations (Fig. 4b and c), and a significant decreasing trend in relative humidity (Fig. 4d) for most of the stations as well. Though not significant at 90% confidence level, precipitation showed varying (increasing and decreasing) trends over all stations with majority of the stations in the north-western part of the country (Seoul, Incheon, Suwon, and Yangpyeong) experiencing higher seasonal increase while many stations in the eastern part (Ulsan, Busan, Jinju, and Miryang) experienced higher seasonal decrease (Table 3). Existing studies reveal that such variations are due to the interaction of heterogeneous topography with the monsoon winds and continental and oceanic

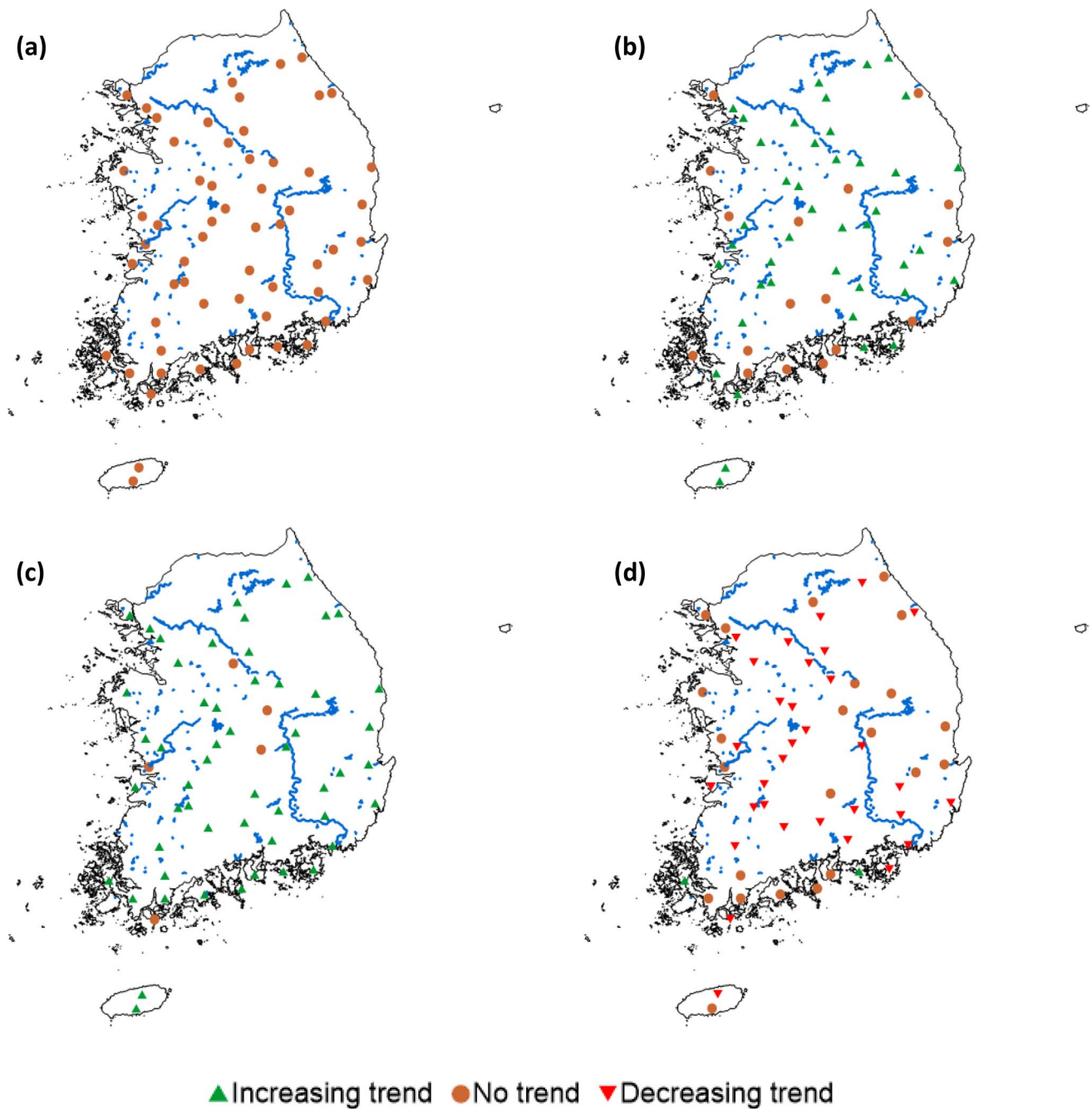


Fig. 4 Spatial distribution of synoptic stations showing seasonal increasing, no trend and decreasing trend at $p \leq 0.1$ for rainfall (a), maximum temperature (b), minimum temperature (c), and humidity (d), during the study period

features (Poudel and Shaw 2016). Soybeans are generally grown under climate conditions ranging between 10 and 35 °C (FAO 2021). The lowest temperature recorded was 10.5 °C at Daegwallyeong station, and the highest temperature was 30.8 °C at Daegu station (Table S1 and S2) all falling within the adaptable range for soybean cultivation. Seasonal trend analysis showed that the temperature changes over the study period were within acceptable

range for soybean growth, with no station having positive minimum and maximum temperature changes exceeding 0.084 °C (Table 3), thus explaining the general increasing yield trend over the study period. However, year-to-year variations in temperature can lead to differences in flowering and thus fluctuations in yearly output as observed in this study. Relative humidity is an essential environmental factor for soybean yield because it controls transpiration

Table 3 Sen's slope values for the seasonal maximum (Tmax) and minimum (Tmin) temperatures, rainfall (Rn) and relative humidity (RH). Statistically significant trends at $p \leq 0.1$ are bolded

No.	Station	Tmax (°C)	Tmin (°C)	Rn (mm)	RH (%)	No.	Station	Tmax (°C)	Tmin (°C)	Rn (mm)	RH (%)
Sen's slope values											
1	Seoul	0.040	0.052	1.358	– 0.247	31	Mokpo	– 0.006	0.028	– 0.286	0.177
2	Incheon	0.037	0.047	1.169	0.010	32	Yeosu	0.004	0.040	– 0.528	– 0.078
3	Suwon	0.054	0.061	1.126	– 0.118	33	Wando	0.084	0.009	– 0.720	– 0.104
4	Ganghwado	0.008	0.044	0.025	– 0.067	34	Suncheon	0.012	0.032	0.507	– 0.052
5	Yangpyeong	0.029	0.075	1.611	– 0.092	35	Jangheung	0.002	0.046	– 0.394	0.025
6	Icheon	0.033	0.022	0.340	– 0.221	36	Haenam	0.026	0.030	– 0.988	– 0.066
7	Sokcho	0.044	0.025	0.000	0.003	37	Goheung	– 0.009	0.036	– 0.895	– 0.005
8	Daegwallyeong	0.065	0.047	– 1.439	– 0.001	38	Uljin	0.030	0.021	0.460	–
9	Chuncheon	0.027	0.052	1.088	– 0.046	39	Chupungyeong	0.026	0.013	– 0.151	–
10	Gangneung	0.019	0.039	– 0.034	– 0.142	40	Pohang	0.017	0.058	0.040	– 0.005
11	Wonju	0.054	0.084	0.595	– 0.278	41	Daegu	0.033	0.055	0.218	– 0.244
12	Inje	0.027	0.049	0.947	– 0.102	42	Yeongju	0.024	0.035	0.308	– 0.079
13	Hongcheon	0.032	0.064	0.610	– 0.238	43	Mungyeong	0.005	0.004	0.167	0.059
14	Chungju	0.030	0.036	– 0.173	– 0.268	44	Yeongdeok	0.025	0.038	– 0.075	– 0.021
15	Cheongju	0.025	0.076	– 0.327	– 0.281	45	Uiseong	0.046	0.038	– 0.130	– 0.011
16	Jecheon	0.020	0.025	0.174	– 0.118	46	Gumi	0.044	0.061	0.612	– 0.153
17	Boeun	0.032	0.052	– 0.536	– 0.198	47	Yeongcheon	0.031	0.033	0.183	– 0.033
18	Seosan	0.013	0.025	– 0.029	0.021	48	Ulsan	0.025	0.039	– 0.635	– 0.103
19	Daejeon	0.014	0.056	– 0.592	– 0.151	49	Busan	0.017	0.035	– 0.624	– 0.094
20	Cheonan	0.030	0.046	– 0.113	– 0.221	50	Tongyeon	0.017	0.023	– 0.151	0.096
21	Boryeong	0.009	0.063	– 0.596	– 0.070	51	Jinju	0.026	0.029	– 0.687	– 0.200
22	Buyeo	0.029	0.044	– 0.240	– 0.206	52	Geochang	0.029	0.045	– 0.339	– 0.044
23	Geumsan	0.037	0.036	– 0.066	– 0.199	53	Hapcheon	0.056	0.031	– 0.267	– 0.209
24	Gunsan	0.034	0.018	– 0.393	0.093	54	Miryang	0.051	0.047	– 0.745	– 0.143
25	Jeonju	0.047	0.042	– 0.352	– 0.103	55	Sancheong	0.006	0.037	– 0.351	– 0.145
26	Buan	0.037	0.058	– 0.643	– 0.167	56	Geoje	0.026	0.044	– 0.645	– 0.167
27	Imsil	0.039	0.043	0.097	– 0.159	57	Namhae	0.023	0.033	– 0.329	– 0.100
28	Jeongeup	0.034	0.063	0.716	– 0.210	58	Jeju	0.027	0.049	– 0.643	– 0.116
29	Namwon	0.014	0.040	– 0.279	– 0.264	59	Seongsan	0.003	0.051	– 0.203	– 0.059
30	Gwangju	0.040	0.050	– 0.125	– 0.176	60	Seogwipo	0.028	0.053	0.477	0.041

at the leaf level and can affect crop water balance. A high relative humidity accompanied by increasing temperature, reduces transpiration and growth, as well as nutrient assimilation (Ferrante and Mariani 2018; Roriz et al. 2014). A reduction in the trend of relative humidity in most of the stations coupled with the increasing temperature thus explains the increasing trend in soybean yield over the study period.

Factors such as government policy, as well as pests and diseases, are difficult to quantify. As a result, the focus of this research is on the relationship between soybean yield and associated climate variable anomalies in order to determine the extent to which climate variables influence soybean yield using correlation and multiple regression analysis, as discussed in the sections that follow.

Relationship between Climatic Variability and National Soybean Yield

Soybean like most other rain-fed crops is affected by both natural and anthropogenic factors. Climate variability that exists in most parts of the country influences crop production (Won et al. 2019), hence a need for an evaluation. Over the course of the growing season, all studied regions displayed different levels of impacts on soybean growth as portrayed in Table 4. However, stations including Icheon, Cheongju, Daejeon, Cheonan, Sokcho, Namwon, Chuncheon, Jecheon, Boeun, Mokpo, Goheung, Uiseong, Sancheong, Wando, Hapcheon, Daegu, Yeongcheon, and

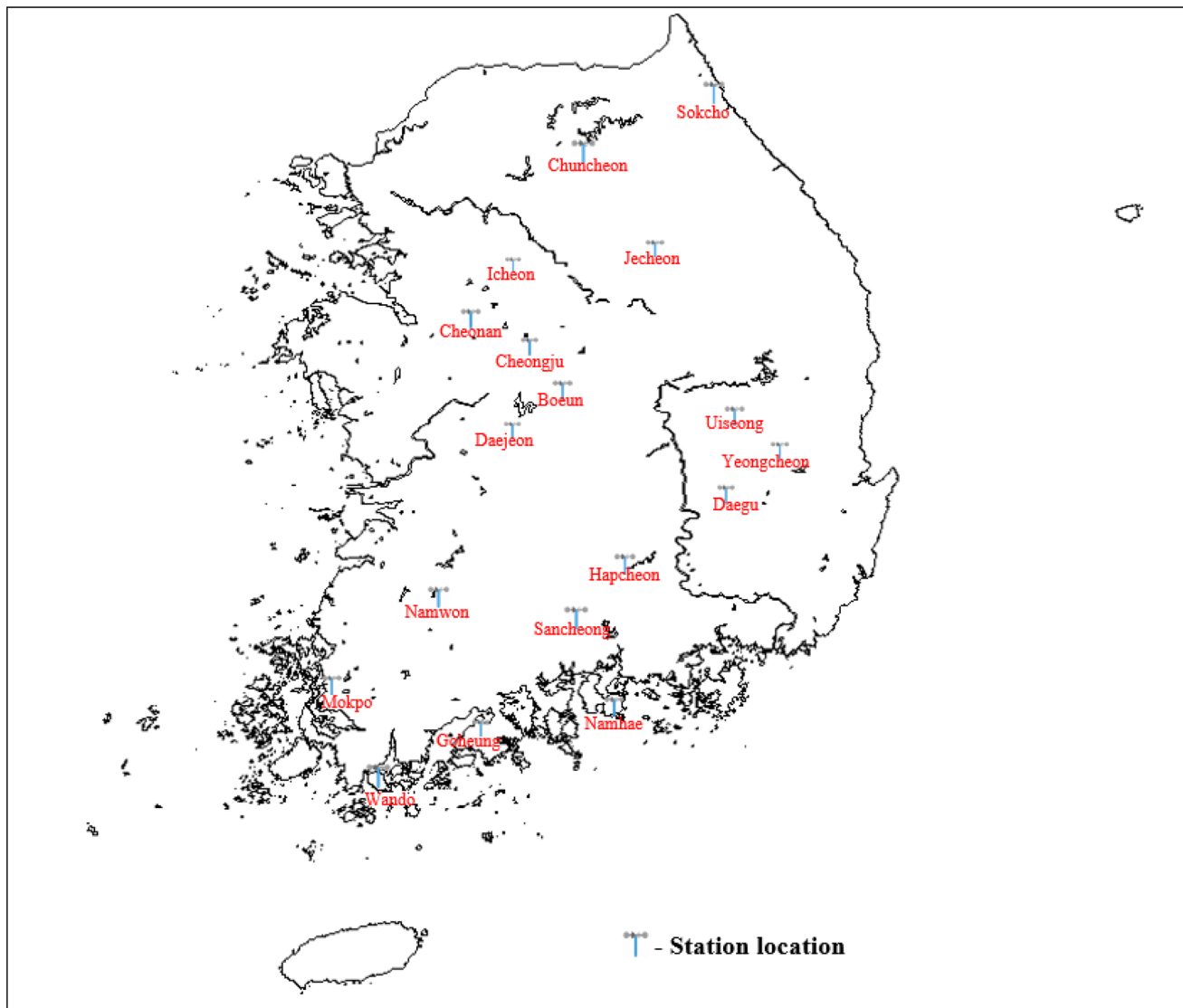


Fig. 5 Major contributors to the national yield based on location-wise correlation

Namhae recorded significant impacts (Fig. 5) implying that they are major contributors to the national yield; hence their climate anomalies influence the national soybean yield.

Generally, minimum and maximum temperatures and rainfall had positive (direct) relationship with the soybean yield as evidenced by statistically significant correlation values of $r = 0.351$, 0.449 and 0.413 respectively, at $P \leq 0.05$ between soybean yield and averaged temperature (minimum and maximum) and rainfall. This shows that the yield of soybean increased with increasing minimum and maximum temperatures, and rainfall. This is understandable since soybean is highly sensitive to climatic conditions during the growing period, hence adequate water coupled with increasing temperature within optimal range would promote growth (Hatfield and Prueger 2015). Relative humidity

however, had a negative (indirect) impact on the soybean yield during the growing season, with a significant correlation of, $r = -0.452$, at $P \leq 0.05$; implying that an increase in relative humidity would result in a decrease in yield (Ali et al. 2017). This is because relative humidity above the optimum level would directly contribute to problems such as increased pest and disease infestation, slow drying of the growing medium, plant stress, quality loss, and overall soybean yield reduction.

Yield Changes due to Seasonal Climate Variability

A multiple regression model was used to ascertain the impact of seasonal climate variability on national soybean yield. Climate variables and yield anomalies were computed using the first-difference time-series, and these

Table 4 Location-wise correlation values of maximum temperature (T_{max}), minimum temperature (T_{min}), rainfall (R_n) and relative humidity (RH) anomalies to national soybean yield

No.	Station	T_{max}	T_{min}	R_n	RH	No.	Station	T_{max}	T_{min}	R_n	RH
Climate Variables											
1	Seoul	0.143	0.101	0.213	-0.099	31	Mokpo	0.384*	-0.051	0.173	0.053
2	Incheon	-0.172	0.061	0.170	0.133	32	Yeosu	0.150	-0.133	0.205	0.101
3	Suwon	0.221	0.112	0.158	-0.214	33	Wando	-0.217	0.351*	0.074	0.004
4	Ganghwado	-0.156	0.039	0.008	0.104	34	Suncheon	0.240	0.003	0.153	-0.150
5	Yangpyeong	0.198	-0.059	0.217	-0.127	35	Jangheung	0.259	-0.145	0.074	0.012
6	Icheon	0.328*	0.023	0.009	0.302	36	Haenam	0.028	-0.162	0.008	-0.203
7	Sokcho	0.053	0.024	0.376*	-0.141	37	Goheung	0.354*	-0.117	-0.014	-0.153
8	Daegwallyeong	-0.129	-0.080	0.305	-0.174	38	Ulsan	0.098	-0.129	0.195	-
9	Chuncheon	0.002	0.009	0.275	-0.342*	39	Chupungyeong	0.152	0.019	0.233	-
10	Gangneung	0.145	0.090	0.278	0.024	40	Pohang	0.057	0.143	0.262	-0.114
11	Wonju	0.202	0.105	-0.082	-0.068	41	Daegu	0.320	0.097	0.333*	0.264
12	Inje	0.037	-0.120	0.279	-0.236	42	Yeongju	0.101	-0.145	0.188	-0.177
13	Hongcheon	0.099	-0.124	0.249	-0.196	43	Mungyeong	0.251	-0.093	0.176	0.196
14	Chungju	0.167	-0.216	0.038	-0.071	44	Yeongdeok	0.155	-0.175	0.250	-0.069
15	Cheongju	0.432**	-0.009	0.098	-0.051	45	Uiseong	0.351*	-0.274	0.241	-0.293
16	Jecheon	0.011	-0.252	0.006	-0.344*	46	Gumi	0.252	-0.020	0.292	0.031
17	Boeun	0.252	-0.187	0.260	-0.349*	47	Yeongcheon	0.216	-0.230	0.361*	-0.219
18	Seosan	-0.106	-0.056	0.036	0.049	48	Ulsan	0.132	0.020	0.085	-0.234
19	Daejeon	0.377*	0.031	0.208	0.352*	49	Busan	0.051	-0.064	0.226	0.072
20	Cheonan	0.407*	0.105	0.067	-0.190	50	Tongyeong	-0.170	-0.070	0.285	0.144
21	Boryeong	0.257	-0.141	-0.014	-0.136	51	Jinju	0.006	-0.160	0.170	-0.029
22	Buyeo	0.033	-0.151	0.081	-0.001	52	Geochang	0.283	-0.218	0.245	0.191
23	Geumsan	0.270	-0.179	0.246	-0.163	53	Hapcheon	0.226	-0.356*	0.181	0.009
24	Gunsan	0.162	0.065	0.089	-0.137	54	Miryang	0.260	-0.149	0.300	-0.239
25	Jeonju	0.222	-0.093	0.152	-0.146	55	Sancheong	0.324*	-0.216	0.121	-0.026
26	Buan	0.106	-0.080	0.049	0.014	56	Geoje	0.291	0.043	0.203	0.125
27	Imsil	0.239	-0.014	0.282	-0.154	57	Namhae	0.066	-0.051	0.347*	-0.008
28	Jeongeup	0.226	0.091	0.195	-0.031	58	Jeju	-0.115	-0.022	0.107	0.090
29	Namwon	0.238	0.121	0.330*n	-0.047	59	Seongsan	-0.023	-0.089	0.110	0.004
30	Gwangju	0.209	0.082	0.226	0.166	60	Seogwipo	0.064	0.067	0.113	-0.123

Statistically significant values are bolded

*Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

anomalies were used to quantitatively estimate the relationships between climate variability and crop yield. The model was developed using significant aggregated seasonal climate indices from various regions. Significant location-wise correlations existed for minimum temperature (Wando and Hapcheon stations), maximum temperature (Icheon, Cheongju, Daejeon, Cheonan, Mokpo, Goheung, Uiseong, and Sancheong stations), rainfall (Sokcho, Namwon, Daegu, Yeongcheon, and Namhae stations), and relative humidity (Chuncheon, Jecheon, Boeun, and Daejeon) to national yield; hence these climate indices were utilized in the building of the model.

The derived regression model is:

$$y = 0.171 + 0.981T_{max} + 0.605T_{min} + 0.117R_n - 0.745RH. \quad (4)$$

y is the predicted soybean yield, T_{max} is the maximum temperature, T_{min} is the minimum temperature, R_n is the rainfall, and RH is the relative humidity.

The yield variance is measured by the constant term in the equation if the climate variables remained constant at the mean period. It also accounts for other factors such as improved seeds, better farm management practices, and introduction of new technology that were excluded from the study. The regression estimates show that climate variables

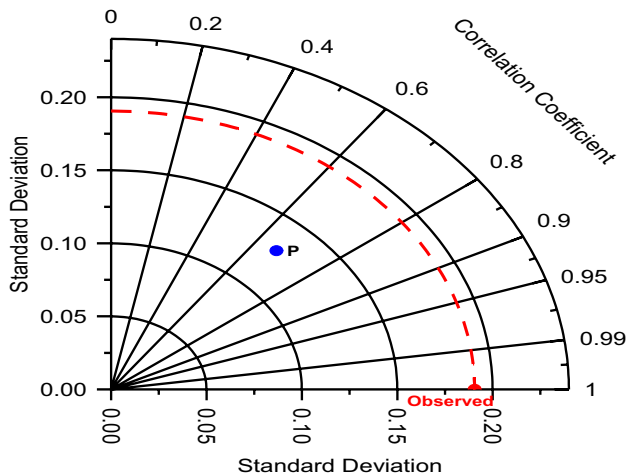


Fig. 6 Model credibility check using the Taylor diagram; the blue dot shows the predicted yield, and the red dot shows the observed yield

account for about 45.5% of the changes in national soybean yield, with an R^2 value of 0.455. Rahman et al. (2017) reported a similar estimate in their study on the impacts of temperature and rainfall variations on rice productivity in major ecosystems of Bangladesh. As illustrated in Eq. 4, one unit change in seasonal maximum temperature will lead to an increase of soybean yield by 0.981 tons/ha, one unit change in minimum temperature will lead to a yield increase by 0.605 tons/ha, one unit change in rainfall will lead to an increase in yield by 0.117 tons/ha, and finally, one unit change in relative humidity will lead to a yield decrease of 0.745 tons/ha. These findings show that soybean yield is sensitive to climate variations, especially temperature changes. A major reason for the positive influence of temperature on soybean yield is the elevated level of CO_2 in South Korea (Adelodun and Choi 2020; Oh et al. 2010). Lee et al. (2020) reports that an increase in temperature, with a concurrent elevation of CO_2 , could positively affect crop productivity and quality. Similarly, Lin et al. (2021) reports that an increase in CO_2 could offset the adverse warmer temperature effect on crop yield. The study on the influencing climatic factors on soybean yield has become of particular importance all over the world owing to the growing food security concerns. As such, studies exist from different regions. Jiang et al. (2011) in their study on the influence of climate change on crop development and yield in China reported a positive influence of warming on the advancement of soybean growth. Novikova et al. (2020), also reported that the warming of regions with temperate climate (like South Korea), increases opportunities for the active development of soybean production, thus supporting the findings of this study.

The credibility of the model was assessed using the Taylor diagram (Fig. 6). A small standard deviation (amplitude of the variation) of 0.13 tons/ha indicates little variability between the observed and predicted yield. In addition, a significant ($P \leq 0.05$) correlation coefficient of 0.68 indicates a close agreement between the observed and predicted yield over the study period, implying the more significant contributions of climate factors to soybean production.

Conclusions

The increasing global warming trend is more visible in mountainous areas (like South Korea) compared to the plains. Thus, climate change will continue to have a significant impact on the food system as observed from the results in this study. During the entire growing season, climate variables had statistically significant differential effects on national annual soybean yield. The interactions of rainfall, temperature (minimum and maximum), and relative humidity could explain 45.5% of the variation in yield. The yield showed an increasing trend over the study period, with high variability due to climate influences. This increase in yield was attributed to the increasing rainfall, coupled with the concurrent optimal increase in temperature (minimum and maximum), and decrease in relative humidity. The regression model thus shows a more positive impact of climate change on soybean production in South Korea.

Organizations and researchers can use the findings of this study to assess current climate variability and fluctuations, as well as their impact on soybean yield. Also, to improve food security, significant adaptation and mitigation strategies should be prioritized based on credible knowledge of the important soybean production areas. In addition, to maintain a sustainable food supply, we urge policymakers and researchers to further evaluate the effects of climate change on soybean yield and make decisions across several spatial scales for both short- and long-term goals in order to adapt to future impacts of climate change.

The main limitation of this study is the aggregation of national climate and yield data, despite the huge diversity existing within the study area. For a better understanding of the patterns and consequences of climate variability on soybean yield, further research with high resolution, grid-based climatology dataset is highly recommended.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s42106-022-00188-2>.

Declarations

Conflict of interest The authors report no conflict of interest.

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