JAST (Journal of Animal Science and Technology) TITLE PAGE

Upload this completed form to website with submission

ARTICLE INFORMATION	Fill in information in each box below
Article Title (within 20 words without abbreviations)	Assessment of weather events impacts on forage production trend of sorghum-sudangrass hybrid
Running Title	Forage production of sorghum-sudangrass hybrid under weather events
Author	Moonju Kim1, Kyungil Sung2
Affiliation	1 Institute of Animal Life Science, Kangwon National University, Chuncheon 24341, Korea 2 Department of Animal Industry Convergence, Kangwon National University, Chuncheon 24341, Korea
ORCID (for more information, please visit https://orcid.org)	Moonju Kim (https://orcid.org/0000-0003-0917-7710) Kyungil Sung (https://orcid.org/0000-0003-1232-3520)
Competing interests	No potential conflict of interest relevant to this article was reported.
Funding sources State funding sources (grants, funding sources, equipment, and supplies). Include name and number of grant if available.	Not applicable.
Acknowledgements	This study was supported by the Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Science and ICT (NRF- 2020R1C1C1004618).
Availability of data and material	Upon reasonable request, the datasets of this study can be available from the corresponding author.
Authors' contributions Please specify the authors' role using this form.	Conceptualization: Kim M. Data curation: Kim M Formal analysis: Kim M. Methodology: Kim M. Software: Kim M. Validation: Sung K. Investigation: Kim M. Writing - original draft: Kim M. Writing - review & editing: Sung K.
Ethics approval and consent to participate	This article does not require IRB/IACUC approval because there are no human and animal participants.

CORRESPONDING AUTHOR CONTACT INFORMATION

For the corresponding author (responsible for correspondence, proofreading, and reprints)	Fill in information in each box below
First name, middle initial, last name	Kyungil Sung
Email address – this is where your proofs will be sent	kisung@kangwon.ac.kr
Secondary Email address	
Address	Gangwondaehakgil 1, Chuncheon 24341, Gangwondo, Korea
Cell phone number	010 3388 8635
Office phone number	+82 033 250 8635
Fax number	+82 033 242 4540

(Unstructured) Abstract (up to 350 words)

This study aimed to assess the impact of weather events on the sorghum-sudangrass hybrid (*Sorghum bicolor* L.) cultivar production trend in the central inland region of Korea during the monsoon season, using time series analysis. The sorghum-sudangrass production data collected between 1988 and 2013 were compiled along with the production year's weather data. The growing degree days (GDD), accumulated rainfall, and sunshine duration were used to assess their impacts on forage production (kg/ha) trend. Conversely, GDD and accumulated rainfall had positive and negative effects on the trend of forage production, respectively. Meanwhile, weather events such as heavy rainfall and typhoon were also collected based on weather warnings as weather events in the Korean monsoon season. The impact of weather events did not affect forage production, even with the increasing frequency and intensity of heavy rainfall. Therefore, the trend of forage production for the sorghum-sudangrass hybrid was forecasted to slightly increase until 2045. The predicted forage production in 2045 will be 14,926 ± 6,657 kg/ha. It is likely that the damage by heavy rainfall and typhoons can be reduced through more frequent harvest against short-term single damage and a deeper extension of the root system against soil erosion and lodging. Therefore, in an environment that is rapidly changing due to climate change and extreme/abnormal weather, the cultivation of the sorghum-sudangrass hybrid would be advantageous in securing stable and robust forage production. Through this study, we propose the cultivation of sorghum-sudangrass hybrid as one of the alternative summer forage options to achieve stable forage production during the dynamically changing monsoon, in spite of rather lower nutrient value than that of maize (*Zea mays* L.).

Keywords (3 to 6): sorghum-sudangrass hybrid; heavy rainfall; typhoons; forage production trend

Introduction

Climate change has been a major interest to various fields of science over the past two decades, including agriculture [1,2]. Particular interest needs to be focused on changes in the frequency and intensity of abnormal climate events that can greatly affect crop production. In Korea, elevating winter-spring temperatures and summer heavy rainfall are considered as significant weather events caused by climate change [3–5]. The quantity of rainfall in the Korean monsoon season accounts for 40–60 % of total average annual rainfall [6], with a high likelihood that the prevalence of torrential rainfall increases with the increasing occurrence of heavy rainfall events. Furthermore, during the monsoon season, the event of typhoons also needs to be looked at because various summer crops have been seriously damaged by typhoon ahead of harvests [7]. In contrast to the relatively short-term rainfall-related weather events, Korean spring droughts can be fatal to forage crops due to their long-term impact. Fortunately, the sorghum-sudangrass hybrid (*Sorghum bicolor* L.) has high adaptability against drought (rainfall range of 200–700 mm) due to its good heat tolerance [8]. Therefore, this study considered, heavy rainfall and typhoon occurrence as the weather events in the monsoon season.

Forage corn (*Zea mays* L.) and sorghum-sudangrass hybrid are typical summer annual forage crops in Korea. In particular, the sorghum-sudangrass hybrid can be harvested multiple times a year. In Korea, the headless type sorghum-sudangrass hybrid is preferred over heading type sorghum-sudangrass hybrid because it is popularly used as whole crops due to the slow hardening of the stem [9]. Thus, to achieve a stable yield, the sorghum-sudangrass hybrid has been widely cultivated as a silage crop where forage crop is hard to produce. Furthermore, due to the reliable regrowth, sorghum-sudangrass hybrid can produce more forage production through additional harvest [10]. For sorghum-sudangrass hybrid that grows at a warmer temperature than silage maize, livestock farmers prefer headless type to heading type in Korea [11]. Cultivation of sorghum-sudangrass hybrid is advantageous due to flexibility of management options. sorghum-sudangrass hybrid can be a useful forage crop due to high forage production, tolerance to environmental stresses, and ratoon capability [12]. Furthermore, sorghum-sudangrass hybrid is tolerant to drought condition. The crop accumulates great amount of lignocellulosic biomass with fermentable sugars and starch [13]. Although forage quality was negatively related to cellulosic biomass production, some headless sorghum-sudangrass hybrids remains longer in a vegetative growth stage and maintain its quality [11]. Furthermore, in terms of production economics, cost per ton of sorghum forage production was the lowest comparing with switchgrass (*Panicum virgatum* L.), reed canarygrass (*Phalaris arundinacea* L.), big bluestem (*Andropogon gerardii* Vitman var. *gerardii*) and alfalfa (*Medicago sativa* L.) [14]. Therefore, sorghum-sudangrass hybrid has been a valuable forage crop.

Typhoon accommodating heavy rainfall damage Korean agriculture during summer, in particular, property damage due to heavy rainfall accounted for about 70% of all agricultural meteorological disasters [15]. In spite of gradual disaster mitigation and prevention measures, meteorological disasters occur every year under various conditions and intensities in the case of heavy rainfall and typhoons [16]. Forage production has been also damaged severely by lodging [17]. According to the international convention [18], rainfall defined by the amount per hour such as drizzle (slow-falling water droplets between 0.2 and 0.5 mm in diameter), light rain (accumulations of 2.5 mm per hour), moderate rain (accumulations of 2.5 to 7.6 mm per hour), and heavy rain (accumulations of over 7.6 mm per hour). Meanwhile, the heavy rainfall also can be defined as the rainfall amount over a given time. According to Lee et al. [19], the daily mean intensity of heavy rainfall was approximately 150–200 mm day^{-1} for 10 continuous-day in Korea. Furthermore, the total heavy rainfall in July was more than 1,000 mm month^{-1}. In particular, it was found that heavy rainfall of 1,000 mm during monsoon season reduces corn production [20]. Hence, it was worth considering both the frequency and the total amount of heavy rainfall during monsoon season in this study. Meanwhile, typhoon is a tropical cyclone having a wind speed near 17 m/s and 200–600 km in diameter [21]. Since the regional impact of typhoons is changeable depending on their path and radius [22], we were interested in local typhoon warnings in this study. The effects of climatic, soil and cultivar on forage production of sorghum-sudangrass hybrid have been assessed by field trials in Korea [23]. In general, the first harvest of sorghum-sudangrass hybrid in Korea is closely related to the monsoon season. Since the estimated forage production decreased after 5 days from the expected optimal harvesting time [24], the length of monsoon season determined by the frequency of heavy rainfall is also an important factor in forage production. Thus, it was recommended to seed and harvest within 5 days to secure a stable yield. Long-term sorghum-sudangrass hybrid yield trends affected by temperature, precipitation, and sunshine duration, the relationship was not clearly evaluated [25]. Hence, research is necessary to understand in the significant weather event impact on forage crop production during summer growing season. The effect of weather is meaningful not only in the form of events, but also in the independent variable itself. Dixon et al. [26], the mean temperature, accumulated solar radiation, mean soil moisture and accumulated precipitation were considered to predict corn yield. Furthermore, GDD, accumulated rainfall and irradiation were considered for modeling yield trend of summer forage crops [25, 27]. Therefore, the prediction of future sorghum-sudangrass production was developed based on climate related sorghum-sudangrass production data appearing in the previous trials.

A time series analysis was applied to the data to estimate yearly climate impacts which is one of the most effective statistical methods [28]. The prediction models developed for vetch (*Vicia sativa* L.), silage maize, sainfoin (*Onobrychis viciifolia* Scop.) and alfalfa in Turkey [29] forecasted forage amount until 2025. However, there was no consideration of climate and weather. For the forage production trend of WCM in Korea [11], heavy rainfall during the monsoon season lead to substantial production reduction. Furthermore, due to the increasing frequency and intensity of heavy rain, forecasted corn production can be reduced by up to 70% of the past 30-years' average. Meanwhile, review on sorghum-sudangrass hybrid without considering the effect of climatic variables confirmed the trend is closely related to the past two years and had no significant relation to the previous three years' production [27]. Thus, to develop more robust prediction, it will be necessary to consider forage production trend of sorghum-sudangrass hybrid along with weather event.

Therefore, this study analyzed the impact of heavy rainfall and typhoon events on the forage sorghum production during monsoon season in the central inland regions of Korea.

Materials and Methods

Data and variables

The raw data (n = 1,076), including the forage production (kg/ha), number of harvests, year, address, seeding and harvesting dates, etc., were collected from the reports on the variety trials conducted by the Rural Development Administration [RDA] of Korea. Usually, the damage caused by heavy rainfall and typhoon in the monsoon season varies considerably depending on local and topographical conditions;

therefore, it was necessary to select a single location for homogeneity of data. Based on the regional classification chart of the Republic of Korea [30], sorghum-sudangrass hybrid is predominantly cultivated in central inland and southern inland regions. Furthermore, it was important role to record long-term data to allow for trends to be detected. Considering these two conditions, Suwon (latitude: 37° 15′ N, longitudinal: 127° 04′ E, n = 388) was selected as a representative central inland region of Korea (1988–2013). Maximum likelihood algorithm was applied to adjust missing year data in the modeling of forage production [31].

The weather data, including temperature, rainfall and sunshine duration, were collected from the Korean Meteorological Administration [KMA] via open-API (application programming interface). For inclusion of the weather event during the monsoon season, rainfall per hour was considered to differentiate heavy rainfall from ordinary rainfalls [11]. Where, the frequency and total amount were considered based on the hourly heavy rainfall and accumulated rainfall in July, respectively. GDD (℃) with the base temperature of 10℃, accumulated rainfall (mm), sum of sunshine duration (hr), heavy rainfall 1 (frequency of over 7.6 mm/hr rainfall amount), heavy rainfall 2 (dummy variable, 1: over 1,000 mm/July, 0: else), and the frequency of typhoon were generated from seeding to harvesting date as a variable in the study.

Statistical analysis

The forage production and weather variables were compiled by the cultivation year to make the data in a time series format. However, the sorting based on field type (upland field or paddy field) and cultivars was impossible because some annual values were undetectable. Since time series analysis can decompose data into seasonality and circularity [32], an autoregressive integrated moving average with exogenous inputs (ARIMAX) model was used in this study to detect yearly production trends of sorghum-sudangrass hybrid according to the following equation [27]:

$$Y_t = \nu + \phi_1 Y_{t-1} + \cdots + \phi_p Y_{t-p} + \varepsilon_t + \theta_1 \varepsilon_{t-1} + \cdots + \theta_q \varepsilon_{t-q} + \beta_1 X_t + \cdots + \beta_r X_{t-r}, \quad (1)$$

where, ν is intercept; Y_t is forage production at year t as the dependent variable; For the independent variables, Y_{t-p} is forage production at year lag p, where the lag is the difference in time. For example, if p is 1, Y_{t-1} indicates forage production at time $t-1$, which is a year before time t. X_t are weather variables (GDD, accumulated rainfall and sunshine duration) and weather event (heavy rainfall 1, heavy rainfall 2 and typhoon); ϕ and θ are the coefficient of time lags in the autoregressive and moving average parts, respectively; ε_q is the white noise at year lag q, which indicates a sequence of random numbers as an unpredictable error. If the white noise is small, other model is no longer needed; β_r is the coefficient of X at year lag r. Firstly, autoregressive of lag p, *AR (p)* is described by the association between forage production over the past p-year. Secondly, the integration of lag d, as *I (d)*, serves to confirm the stationarity that enable a stable estimation of the forage production trend. Thirdly, the moving average of lag *q*, as *MA (q)*, is formed from the linear combination of forage production's white noise. It indicates a simple and common type of smoothing used in forage production forecasting. Finally, *X* is used to explain the impacts of weather variables and/or events on current forage production, such as GDD, accumulated rainfall, sunshine duration, heavy rainfall 1, heavy rainfall 2 and typhoon. Sorghum-sudangrass forage production trend was described by past year, lag time, and moving average of lag *q* of ARIMA (p, d, q), and the impacts of weather variables and/or events were estimated using independent variables. Outlier data were eliminated using box-plot for the application of consistent forage production trends.

For optimum ARIMAX model selection, root mean square error (RMSE), R^2, maximum absolute percentage error (MAPE) and a Ljung-Box Q test were considered. Higher R^2 value and lower error values of RMSE and MAPE were referred for a good fit [28]. Furthermore, the *p*-value greater than 0.05 of the Ljung-Box *Q* test was applied to confirm insignificance of residuals from the ARIMA model [33]. The proc ARIMA of SAS 9.4 (SAS Institute Inc., Cary, NC) was used for forage production modeling.

Results

Assessment of the climate impact on the sorghum-sudangrass hybrid forage production

To consider the impact of weather variables and weather events on sorghum-sudangrass hybrid forage production via ARIMAX model, it was necessary to estimate the forage production trend and weather. The GDD, accumulated rainfall and sunshine duration on forage production were significant as independent variables in the regression analysis (Table 1); however, the variance inflation factor of sunshine duration was greater than 4, meaning that this independent variable's contribution to sorghum-sudangrass forage production was distorted probably due to multicollinearity. Therefore, sunshine duration should be ignored in the model.

A yearly trend for the GDD and accumulated rainfall can be seen in Fig. 1a. The trends in forage production and GDD looked similar over the whole time period (1989–2013), especially between 1992–2007 and 2010–2013. Similar trends between forage production and accumulated rainfall were observed in some cases, but conflicting trends were suspected in most. For example, the accumulated rainfall trend in 2002–2009 showing rainfall of below 1,000 mm was similar to the forage production trend. In contrast, when accumulated rainfall was over 1,000 mm, forage production was found to decrease, with the years of 1990, 1995, 1998, 2010, 2011 and 2012 standing out. Therefore, it was hypothesized that the GDD's trend was associated to the overall forage production trend and the accumulated rainfall trend was also correlated to the forage production trend depending on the specific range of rainfall.

The forage production trend was evaluated by ARIMA to determine the impact of weather events (Table 2). Unlike the GDD, rainfall amount, and sunshine duration, the three weather events did not contribute to the variance of the forage production ($p > 0.05$). This insignificance of the weather event probably reasoned from insufficient data of the extreme weather events. Similar to the heavy rainfall event, typhoon frequency did not contribute to the modeling of forage production (p = 0.56). The yearly trends of heavy rainfall and typhoon can be seen in Fig. 1b. heavy rainfall 2 was not considered because it was dummy scale. No meaningful association could be found between the trend in forage production influenced by heavy rainfall 1 and typhoon. The long-term field trial data of forage sorghum-sudangrass hybrid demonstrated some production peaks followed a similar pattern with GDD from 1992 to 2007, but demonstrated a reversed pattern with the accumulated rainfall (Fig. 1a).

Comparison of forage production models considering weather variables and/or events

From each trend in Fig. 1, it was hypothesized that the weather variables and events are related to the forage production trends. Considering the impacts of weather variables and extreme weather events on sorghum-sudangrass forage production, five models were developed (Table 3). The model 1 was developed based on time without considering climate variables and events. The forage production trends considering the impact of GDD or both GDD and accumulated rainfall presented in models 2 and 3, respectively. Inclusions of weather variables did not improve the sorghum-sudangrass forage production models. The estimates of the independent variables were significant only in models 2 and 3. To assess the potential sorghum-sudangrass forage production influenced by weather events, the impacts of heavy rainfall 2 (1: over 1,000 mm during monsoon season, 0: else) and typhoon (1: event occurrence, 0: else) were estimated in models 4 and 5, respectively. In models 2 and 3, estimates of GDD were positive while those of rainfall were negative, which support the yearly production trends appearing in Fig. 1a. Additionally, based on model fitness, other tested models adopting weather variables were not improved from model 1. The weather events during the monsoon season (heavy rainfall 2 in model 4 and typhoon in model 5) had no significant evidence implying potential impact on the current sorghum-sudangrass forage production (p > 0.05). Based on the Ljung-Box Q test, the model fitness of #2, 4 and 5 were inacceptable (p < 0.05). Although all the modeling attempts including GDD, accumulated rainfall, and extreme weather events did not substantially improve the model, a forage production model of sorghum-sudangrass hybrid may consider GDD and accumulated rainfall as presented in model 3 as following:

$$Y_t = (1 - 0.37)Y_{t-1} + 0.37Y_{t-2} + 6.88GDD_t + 7.32GDD_{t-1} - 3.55RA_t - 3.56RA_{t-1} \quad ,$$

where Y_{t-i}, GDD_{t-i} and RA_{t-i} are equivalent to forage production, GDD and RA (accumulated rainfall) at $t - i$ time, respectively. i is time order; zero means the current point in time. The forage production trend was a first-order in the AR model with one order of non-seasonal differencing. Even though it looked like AR (2) because of the second-order term (Y_{t-2}). Therefore, GDD (1) and RA (1) had the same order of AR in forage production.

Forecasting the forage production trend of a sorghum-sudangrass hybrid with considering weather variables

With considering GDD and accumulated rainfall, the normality test demonstrated symmetrical data distribution probability density function of the kernel (Fig. 2a). To check the prediction performance based on the model 3, the expected forage production was plotted against the observed forage production (Fig. 2b). Compared to a diagonal line with a 1:1 incline, the majority of the data points were located within the 95% confidence range. Furthermore, in the residual diagnosis based on the autocorrelation function, the residual was close to the white noise. Therefore, the model 3 was judged as being suitable for forecasting future forage production trends of sorghum-sudangrass hybrid with considering weather variables. Based on the model 3, the forage production was forecasted from 2014 to 2045 (Fig. 3). The forecasted forage production (kg/ha) values were 14,908.06 ± 5,058.72, 14,904.43 ± 5,420.33, 14,909.66 ± 5,754.48, 14,915.13 ± 6,070.15, 14,920.60 ± 6,370.19 and 14,926.09 ± 6,656.72 for the years 2020, 2025, 2030, 2035, 2040 and 2045, respectively. The future trend of forage production was close to the flat shaped.

Discussion

The impacts of weather events (heavy rainfall and typhoon), GDD and accumulated rainfall on sorghum-sudangrass hybrid forage production demonstrated potential in the development of yield prediction model. The extreme weather events tested in this study did not appear as a major sorghum-sudangrass hybrid forage production determination; however, this does not mean the irrelevancy of those weather factors with the forage production. Since the reduction of forage production caused by the weather factors are so erroneous, the accumulation of organized field data is required for future advanced model development. Perhaps, it is necessary to organize forage production damage caused by the type, which can be caused by heavy rainfall and strong winds. The correlation analysis indicated a weak relationship between heavy rainfall 1 and typhoon (Spearman's r = 0.41*), which has been observed through heavy rainfall associated with typhoon. As previously reviewed, the effect of heavy rainfall and typhoon could not be confirmed through the long-term field trial data because of the insufficient sorghum-sudangrass hybrid cultivation data in the year when extreme summer weather conditions occurred. Extreme weather lasts only a period of time, which may impact crop growth temporarily. The Korean monsoon season lasts 20 to 30 days in general. Forage sorghum-sudangrass hybrid is harvested multiple times, therefore, the lodged sorghum-sudangrass hybrid can be harvested, and later re-growing forage recovers the whole season production [10, 34]. Thus, even if the damage is caused by heavy rainfall accompanied by typhoon, it will be difficult to separate the damage from the impact on total forage production. Sorghum is known for strong drought tolerance than corn due to its deeper spreading root systems, and also tolerant to over 12.7 mm/hr rainfall [35]. According to Venuto and Kindiger [36], a single cut was more productive than the two-cut system for the photoperiod- and/or thermosensitive genotype sorghum-sudangrass hybrid. As reviewed through some forage sorghum-sudangrass field tests, single harvest can be efficient than multiple harvests for greater biomass accumulation. However, distribution of production risk during the monsoon season may justify multiple harvests throughout the sorghum-sudangrass growing season.

The effect of temperature was negative in a study that confirmed the forage production trend of sorghum-sudangrass hybrid in Korea [25]. They did not distinguish regions with different climates. It implies that impact of weather variables could be confounded due to poor data homogeneity. The optimum mean temperatures in the growing period for the highest yield are in the range of 23.89–26.67 °C [37]. The range of mean temperature during growing period was in Suwon (37° 15′ N, 127° 04′ E) was 20.90–24.60 °C, it indicates that it was at the lower limit of the optimum range. Sorghum-sudangrass hybrid is known to grow well from southern to central region in Korea [38]; however, we confirmed that regional classification is necessary to accurately estimate the impact of weather on forage production without the confounded effect. The mean accumulated rainfall in Suwon (37° 15′ N, 127° 04′ E) between 1988 and 2013 was 998.81 ± 264.90 mm, which was greater than the required rainfall amount (368.3–653.0 mm) for the growth and development of sorghum-sudangrass hybrid [35]. According to Chemere et al. [25], the annual precipitation in Korea was 956.9 mm, and it also found to be excessive for sorghum-sudangrass hybrid. The impact of accumulated rainfall on the forage production was estimated to be negative in both regression and time series modeling, indicating that some negative impact of rainfall on the sorghum-sudangrass hybrid forage production. Therefore, based on significant GDD and accumulated rainfall on forage production, but insignificant impact of the extreme weather events, the rainfall over longer period may be a greater impact factor than short term extreme weather events.

Finally, at any point of the forage production, only the past two years' forage production was effective, and the impacts of forage production older than three years were not detected. Furthermore, the prediction of forage production with the relationship with GDD and accumulated rainfall, the variation range was small, however, there was a strong correlation between GDD and increasing forage production. In this study, the projected forage production in 2045 considers climate variability rather than weather events. Hence, this implies a stable forage production of sorghum-sudangrass hybrid in the future because of insignificant contribution of extreme weather events on sorghum-sudangrass hybrid, reduction of forage production risk through multi-harvesting is more promising in Korea. Based on the forage production trend considering the trends of GDD and accumulated rainfall (model 3), the forage production of sorghum-sudangrass hybrid in future was forecasted to be unchanged due to the simple pattern (single up-down). Furthermore, the positive impact of GDD and the negative impact of accumulated rainfall were offset in the forage production forecast. In future, it is necessary to interest in the impact of GDD in the long run than the short-term impact of accumulated rainfall. While the annual forage production was increasing in the historical data, the forecasted forage production was close to flat shaped trend. The future trend is determined by the trends of GDD and accumulated rainfall, and it implies that the negative impact of accumulated rainfall in particular was greater than expected. Meanwhile, if temperature of the climate change scenarios such as representative concentration pathways (RCP) scenarios were considered to GDD of model 3 in forecast, the forecasted forage production will be higher due to increasing temperature. However, in the RCP 8.5, the mean temperature is expected to increase by 4.8 ℃ by the end of the 21st century, which is over to the upper limit of appropriate temperature for the growth and development of sorghum-sudangrass hybrid. Therefore, further study on yield forecasting and simulation using various RCP scenarios is currently underway.

In conclusion, the present study supported to hypothesis that the heavy rainfall and typhoons in Korean monsoon seasons was not enough to damage in forage production of sorghum-sudangrass hybrid. However, if the difference in forage production between frequencies exceeds 3,000 kg/ha, the damage caused by heavy rainfall and typhoons will be significant. No clear evidence of damage on annual forage production of sorghum-sudangrass hybrid due to extreme heavy rainfall and typhoons events in short term was confirmed in this study due to insufficient data about multiple harvesting management. Under the imminent climate change, development of harvest management and fertilization strategy for sorghum-sudangrass hybrid is necessary to secure consistent forage production.

Acknowledgments

This study was supported by the Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Science and ICT (NRF- 2022R1C1C1004618). We are grateful to (Mr.) Hyunwook Jo, (Mr.) Jiyung Kim and (Prof.) Byong-Wan Kim for cooperation during the study.

References

1. Iglesias A, Erda L, Rosenzweig C. Climate change in Asia: a review of the vulnerability and adaptation of crop production. Dordrecht, Netherland: In Climate Change Vulnerability and Adaptation in Asia and the Pacific, Springer; 1996. p.13–27.

2. Fischedick M, Roy J, Acquaye A, Allwood J, Ceron JP, Geng Y, et al. 2014. Industry. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, England: Cambridge University Press; 2014. p.739–810

3. Kang K, Lee D, Na Y, Sim K, Choi I, Lee C, et al. Climate change and Agriculture in Korea, 33rd ed. Seoul, Korea: Rural Development Administration; 2011. p. 1–25.

4. Kim S, Park CK, Kim MK. The regime shift of the northern Hemispheric circulation responsible for the spring drought in Korea. J Kor Meteorol Soc. 2005;41(4):571–585.

5. Park TW, Ho CH, Jeong SJ, Choi YS, Park SK, Song CK. Different characteristics of cold day and cold surge frequency over East Asia in a global warming situation. J Geophys Res Atmos. **2011;** 116(D12).

6. Lee S, Kwon WT. A variation of summer rainfall in Korea. J Kor Geogr Soc. **2004;**39(6):819–832.

7. Intergovernmental Panel on Climate Change [IPCC]. Climate Change 2007: Synthesis Report. Contribution of Working Group I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. Geneva, Switzerland: IPCC; 2007. p. 104.

8. Blum A, Sullivan CY. The comparative drought resistance of landraces of sorghum and millet from dry and humid regions. Ann Bot. 1986;57(6):835–846.

9. Kim JD, Kwon CH, Kim HJ, Park JG, Lee BS, Bing GS, Moon ST. Comparison of agronomic characteristics, forage yield and quality of sorghumxsudangrass hybrid. J Kor Soc Grassl Forage Sci. 2002;22(4):297–302.

10. Choi GJ, Lee SH, Lee KW, Ji HC, Hwang TY, Kim KY. Comparison of Growth Characteristics, Productivity and Feed Values between Varieties of Sudangrass and Sorghum-Sudangrass Hybrids. J Kor Soc Grassl Forage Sci. 2017;37(1):92–99.

11. Lee JK, Kim JG, Shin DE, Yoon SH, Kim WH, Seo S, Park GJ. Effects of cutting frequency on yield and nutritive value between heading and headless varieties of sorghum x sudangrass hybrid. J Kor Soc Grassl Forage Sci. 2000;20(4):237–242.

12. Venuto B, Kindiger B. Forage and biomass feedstock production from hybrid forage sorghum and sorghum–sudangrass hybrids. Grassl Sci. 2008;54(4):189-196.

13. Rooney WL, Blumenthal J, Bean B, Mullet JE. Designing sorghum as a dedicated bioenergy feedstock. Biofuel Bioprod Biorefin. 2007;1(2):147-157.

14. Hallam A, Anderson IC, Buxton DR. Comparative economic analysis of perennial, annual, and intercrops for biomass production. Biomass Bioenergy 2001;21:407–424.

15. Song I, Song JH, Kim SM, Jang MW, Kang MS. Spatial distribution and regional characteristics of meteorological damages to agricultural farms in Korea. J Kor Soc Agric Engin. 2012;54(6):45–52.

16. Ryu H, Choi M, Cho M, Yu I, Kim S. Damage index estimation by analysis of meteorological disasters on. Inter J Agric Biolog Engin. 2019;12(5):58-63.

17. So YS, Adetimirin VO, Kim SK. Observational study on the recovery from root lodging at flowering time and yield reduction in maize (Zea mays L.). Plant Breed Biotech. 2013;1(2):171–177.

18. Britannica, Britannica Visual Dictionary, 2012. Available online: https://www.britannica.com/science (accessed on 10 January 2021).

19. Lee DK, Kim HR, Hong SY. Heavy rainfall over Korea during 1980~ 1990. Kor J Atmos Sci. 1998;1(1):32–50.

20. Kim M, Chemere B, Sung K. Effect of Heavy Rainfall Events on the Dry Matter Yield Trend of Whole Crop Maize (Zea mays L.). Agric. 2019;9(4):75.

21. Barry RG, Chorley RJ. Atmosphere, weather and climate, 8th edition. London and NY: Routledge; 2009.

22. Moon IJ, Choi ES. A definition and criterion on typhoons approaching to the Korean peninsula for the objective statistical analysis. Atmos. 2011;21(1):45–55.

23. Peng J, Kim M, Sung K. Yield prediction modeling for sorghum–sudangrass hybrid based on climatic, soil, and cultivar data in the Republic of Korea. Agric. 2020;10(4):137.

24. Kim M, Kim JY, Sung K. The optimum seeding and harvesting dates of sorghum–sudangrass hybrid (Sorghum bicolor L.) via optimum moving response surface methodology. Grassl Sci. 2021;67:3–11.

25. Chemere B, Kim J, Lee B, Kim M, Kim B, Sung K. Detecting long-term dry matter yield trend of sorghum-sudangrass hybrid and climatic factors using time series analysis in the Republic of Korea. Agric. 2018;8(12):197.

26. Dixon BL, Hollinger SE, Garcia P, Tirupattur V. Estimating corn yield response models to predict impacts of climate change. J Agric Resour Econ. 1994;58-68.

27. Kim M, Jo MH, Chemere C, Sung K. Determination of Trend in Dry Matter Yield of Sorghum-sudangrass Hybrid (Sorghum bicolor L.) in Central Inland of Korea via Time Series Analysis. Ann Resour Sci. 2021;32(2):1–8.

28. Shumway RH, Stoffer DS, Stoffer DS. Time series analysis and its applications (Vol. 3). New York, USA: springer; 2000.

29. Agirbas NC, Celik S, Sapmaz K. Modeling forage crops production using the time series method. Fresenius Environ Bull. 2019;28(11):7763-7776.

30. Ko JW, Baek HJ, Kwon WT, Park JY. The characteristics of spatial distribution of temperature and regionalization in Korea. J Clim Res. 2006;1(1):3–14.

31. Jones RH. Maximum likelihood fitting of ARMA models to time series with missing observations. Technometrics 1980;22(3):389–395.

32. Pai PF, Lin KP, Lin CS, Chang PT. Time series forecasting by a seasonal support vector regression model. Expert Syst Appl. 2010;37(6):4261-4265.

33. Box GE, Jenkins GM, Reinsel GC, Ljung GM. Time series analysis: forecasting and control. Hoboken, New Jersey: John Wiley & Sons; 2015.

34. Ji HC, Lee SH, Yoon SH, Kwon OD, Choi GJ, Kim WH, ..., Lim YC. Growth, forage production and quality of Sorghum, Sorghum× Sudangrass and Sudangrass Hybrids at paddy field in southern region of Korea. J Kor Soc Grassl Forage Sci. 2010;30(2):109-114.

35. Sharma OP, Kannan N, Cook S, Pokhrel BK, McKenzie C. Analysis of the effects of high rainfall in Texas on rainfed sorghum yields. Water 2019;11(9):1920.

36. Venuto B, Kindiger B. Forage and biomass feedstock production from hybrid forage sorghum and sorghum–sudangrass hybrids. Grassl Sci. 2008;54(4):189-196.

37. Roth GW, Harper JK. Agronomy fact 48: forage Sorghum. University Park, Pennsylvania, USA: Penn State Extension, Ag Communications and Marketing, Pennsylvania State University; 1995.

38. Yoon SH, Kim JG, Jeong ES, Sung SH. The study on double cropping system for organic forage production in middle part of Korea. J Kor Soc Grassl Forage Sci. 2007;27(4):275-280.

Tables and Figures

Table 1. Regression of weather variables against dry matter yield of sorghum-sudangrass hybrid.

Weather variables	**Estimate**	***p*-Value**	**Variance inflation factor**
Constant	2,200.65	0.28	
Growing degree days	13.72	< 0.01	3.62
Rainfall amount	-7.49	< 0.01	1.88
Sunshine duration	-16.82	< 0.01	4.53

Table 2. The impact of weather event on sorghum-sudangrass hybrid forage production during Korean monsoon season.

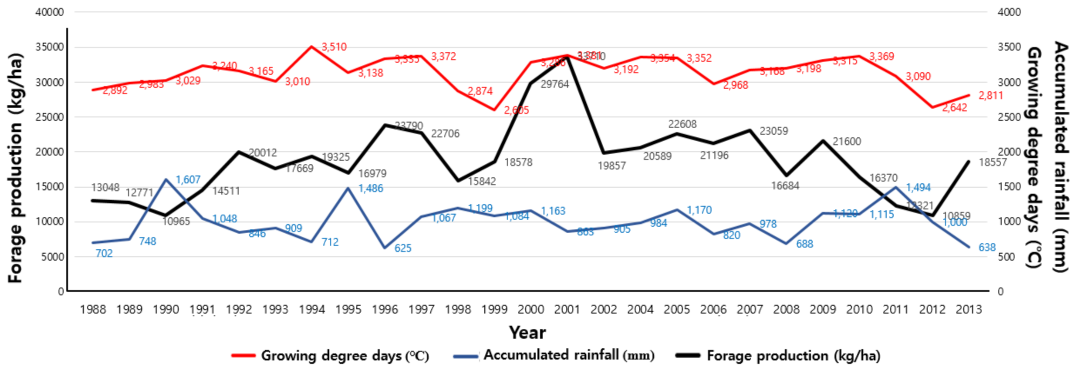
Weather events	Frequency	Sum of dry matter yield (kg/ha)	Test
Heavy rainfall 1[1]	Less 10 (n = 10)	19,506.80 ± 1,720.91	*F* = 0.09 (*p* = 0.92)
	10-20 (n = 12)	18,598.75 ± 1,708.87	
	Over 20 (n = 3)	18,372.33 ± 3,027.91	
Heavy rainfall 2[2]	0 (n = 13)	20,020.54 ± 1,461.11	*F* = 1.04 (*p* = 0.31)
	1 (n = 12)	17,758.58 ± 1,622.83	
Typhoon	0 (n= 2)	17,324.00 ± 4,276.01	*F* = 0.66 (*p* = 0.56)
	1 (n = 3)	24,334.00 ± 8,643.23	
	2 (n = 5)	18,194.40 ± 4,174.11	
	3 (n = 5)	17,985.00 ± 4,235.48	
	4 (n = 4)	17,799.25 ± 5,001.15	
	5 (n = 6)	18,937.67 ± 6,404.31	

[1] Over 7.6 mm per hour, [2] dummy scale (1: over 1,000 mm in Korean monsoon season, 0: else).

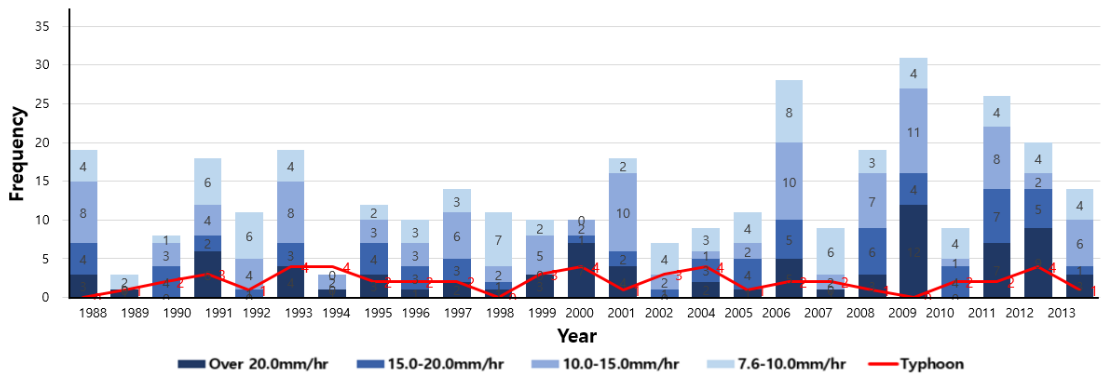
Table 3. Time series models analysis on forage production of sorghum-sudangrass hybrid with weather variables or some extreme weather events (heavy rainfall and typhoon) as independent variables.

Models	Variables		Estimate	R^2	RMSE	MAPE	Ljung-Box Q
1	Forage production (kg/ha)	intercept	-61.11	0.7705	2,941.91	12.69	22.74
		AR 1	-0.45*				(p = 0.158)
		D	1				
2	Forage production (kg/ha)	intercept	1,568.90	0.6057	3,784.55	14.80	28.06 (p = 0.045)
		AR 1	-0.46*				
		D	1				
	GDD (℃)	AR 0	6.16*				
		AR 1	6.65*				
3	Forage production (kg/ha)	intercept	1,390.25	0.6101	3,773.65	14.71	26.25
		AR 1	-0.37				(p = 0.057)
		D	1				
	GDD (℃)	AR 0	6.88*				
		AR 1	7.32*				
	Accumulated rainfall (mm)	AR 0	-3.55*				
		AR 1	-3.56*				
4	Forage production (kg/ha)	intercept	1,568.47	0.6058	3,789.21	14.79	27.92
		AR 1	-0.37				(p = 0.046)
		D	1				
	GDD (℃)	AR 0	6.18				
		AR 1	6.66				
	Heavy rainfall 2 = 1 (over 1,000 mm)		-71.09				
5	Forage production (kg/ha)	intercept	1,416.63	0.6061	3,787.84	14.72	28.20
		AR 1	-0.37				(p=0.043)
		D	1				
	GDD (℃)	AR 0	6.15				
		AR 1	6.69				
	Typhoon = 1 (frequency ≥ 1)		-347.74				

RMSE: Root mean square error, MAPE: mean absolute percentage error, AR: autoregressive- to forecast the dry matter yield using a linear combination of past value, D: differencing time lag- to make a non-stationary time series stationary for dry matter yield, GDD: growing degree days, *$p < 0.05$.

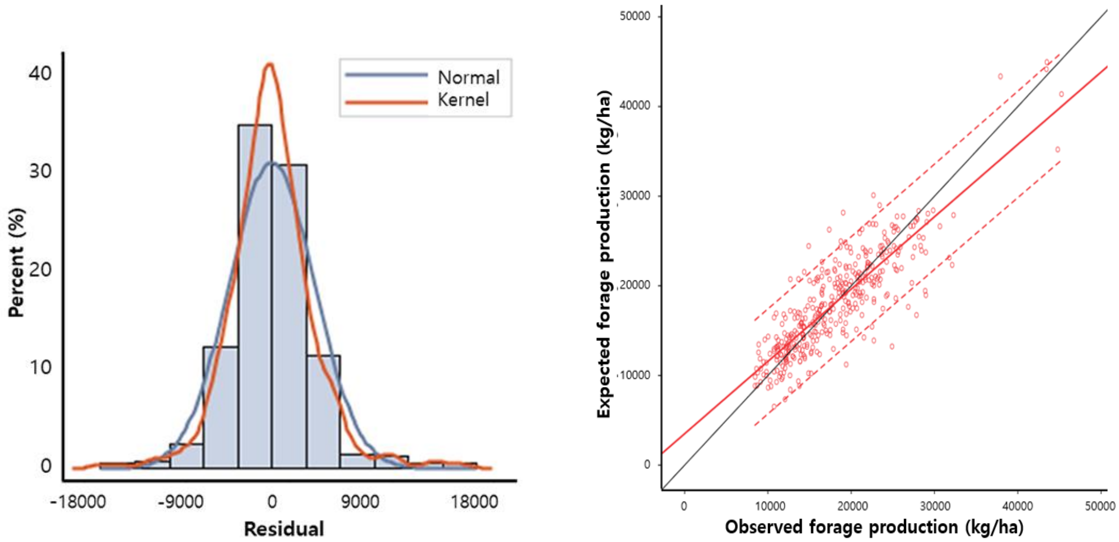


(a)



(b)

Figure 1. Trend of weather variables by year in the central inland regions of Korea (1988–2013): (a) climate variables related to growth and development, (b) weather events during Korean monsoon season.



(a) (b)

Figure 2. Model fitness of the forage production trend considering growing degree days and accumulated rainfall for forage production trend of sorghum-sudangrass hybrid (model 3): (a) histogram for diagnosis of residuals, (b) scatter plot between observed and expected dry matter yield.

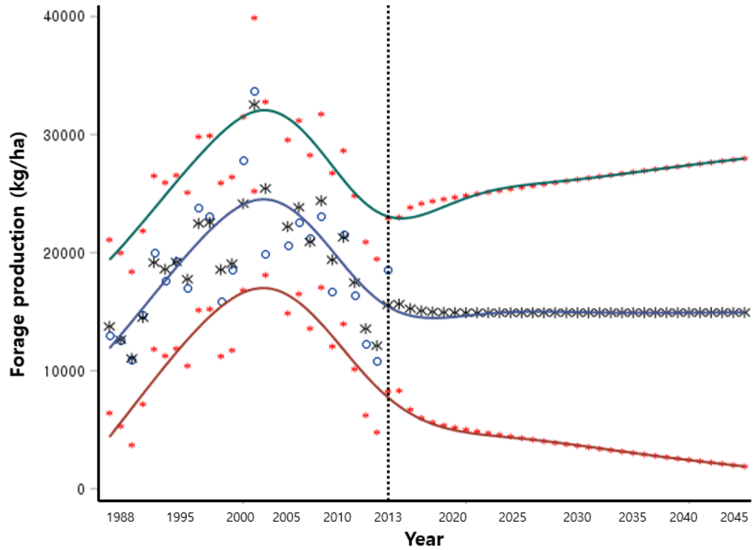


Figure 3. The forecasted forage production of sorghum-sudangrass hybrid with a 95% confidence interval considering growing degree days and rainfall amount (model 3) in the central inland regions of Korea (1988–2045): upper limit: green colored line, mean line: blue colored, low limit line: red line.