# Assessment of Causality between Climate Variables and Production for Whole Crop Maize Using Structural Equation Modeling

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# Assessment of causality between climate variables and production for whole crop maize using structural equation modeling

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**Key words**: whole crop maize; causality; climate; production; silking stage; structural equation modeling

## Abstract
This study aimed to assess the causality of different climate variables on the production of whole crop maize silage (*Zea mays* L.; WCM) in the central inland region of the Republic of Korea. Furthermore, the effect of these climate variables was also determined by looking at direct and indirect pathways during the stages before and after silking. The WCM metadata (n = 640) were collected from the Rural Development Administration's reports of new variety adaptability from 1985–2011 (27 years). The climate data was collected based on year and location from the Korean Meteorology Administration's weather information system. Causality, in this study, was defined by various cause-and-effect relationships between climatic factors, such as temperature, rainfall amount, sunshine duration, wind speed and relative humidity in the seeding to silking stage and the silking to harvesting stage. All climate variables except wind speed were different before and after the silking stage, which indicates the silking occurred during the period when the Korean season changed from spring to summer. Therefore, the structure of causality was constructed by taking account of the climate variables that were divided by the silking stage. In particular, the indirect effect of rainfall through the appropriate temperature range was different before and after the silking stage. The damage caused by heat-humidity was having effect before the silking stage while the damage caused by night-heat was not affecting WCM production. There was a large variation in soil surface temperature and rainfall before and after the silking stage. Over 350 mm of rainfall affected dry matter yield (DMY) when soil surface temperatures were less than 22°C before the silking stage. Over 900 mm of rainfall also affected DMY when soil surface temperatures were over 27°C after the silking stage. For the longitudinal effects of soil surface temperature and rainfall amount, less than 22°C soil surface temperature and over 300 mm of rainfall before the silking stage affected yield through over 26°C soil surface temperature and less than 900 mm rainfall after the silking stage, respectively.

## Introduction
In the Republic of Korea, whole crop maize (*Zea mays* L.; WCM) and soybeans account for 60% of total feedstock use, and its self-sufficiency rate is around 1%. Therefore, a large proportion of the ingredients in feedstock need to be imported (Morgan, 1994). As the main silage resource in the Republic of Korea, WCM cultivation area totals 13,000 ha, and the amount produced was 228,000 tons in 2018 (28.79 % of the total summer forage crop), according to annual statistics of forage supply of the Rural Development Administration (RDA). The self-sufficiency rate of high quality-forage is not as high as that of dairy farming and stands at less than 30% due to the weak base of forage production. In counties with a high dependency on imports, such as the Republic of Korea, it is important to be able to predict forage production to ensure flexibility between domestic production and importation.

In general, a cause-and-effect relationship refers to a direct relationship between a single cause and a single effect. In this study, causality was defined as a characteristic of a network consisting of many cause-and-effect relationships. Therefore, causality in complex structures, which include both direct and indirect relationships, should be distinguished from the cause-and-effect relationship seen in simple structures. Furthermore, causality was generated by analyzing the relationship between various causes, mediators and effects (Jöreskog and Sörbo, 1996). Structural equation modeling (SEM) is a statistical technique that identifies causality between different factors and consists of two parts: The measurement part where common characteristics are extracted to generate common factors from the variables, and a structural part where connections are set between the extracted common factors (Van Montfort et al., 2004). This process creates a big network where balance needs to be kept between the high degree of model fitness and the parsimony to allow for easy interpretation. There is a clear relationship between agricultural climatic factors and crop production, therefore, it is advantageous to form a causality network to estimate the effects each climatic factor has on crop production.

For summer forage crops, it is difficult to classify their growing periods by season due to continuity of growth and development across seasons. In this study, the longitudinal characteristics were considered by taking into account the crop's growth stage instead of which season it was. In general, the growth stages of WCM have divided into two stages: the vegetative stage and the reproductive stage; where the reproductive stage starts after the silking stage (McWilliams et al., 1999). This silking stage is important since this is when kernel fertilization, support ear weight and kernel fill are all determined. Furthermore, climatic conditions during the stage of 50% silking are critical to the yield and quality of WCM (Butts-Wilmsmeyer et al., 2019). Therefore, for WCM silage, the longitudinal characteristics were determined before and after the silking stage.

Therefore, this study aimed to assess the causality of climatic factors on WCM production using SEM by looking at the stages before and after silking. In addition, the appropriate range of climatic factors for good WCM production was determined based on major causality.

## Methods and Study Site

The raw WCM data (n = 993) which includes dry matter yield (DMY, kg/ha), fresh matter yield (FMY, kg/ha), total digestible nutrients yield (TDNY, kg/ha), year, location, seeding date, silking date and harvesting date were collected from the reports of new variety adaptability of the Rural Development Administration (RDA) for 1985–2011 as metadata. For the homogeneity of data, the central inland region (n = 656) was selected according to the classification criteria of Ko et al. (2006); where, Cheonan (36°48'N, 127°9'E), Icheon (37°16'N, 127°26'E) and Suwon (37°17'N, 127°0'E) all belong to the central inland region. Climate data for the WCM metadata were collected from the weather information systems of the Korean Meteorological Administration (KMA). This data included daily temperature, rainfall, wind speed and sunshine duration and was categorized by year and location. The climate information was matched based on cultivation location and year of cultivation via open-API (application programming interface).

The following climate variables were generated for the seeding–silking (SS) stage and silking–harvesting (SH) stage as follows: growing degree days over 10°C (SSGDD and SHGDD, °C), highest temperature (SSHT and SHHT, °C), lowest temperature (SSLT and SHLT, °C), soil surface temperature (SSST and SHST, °C), relative humidity (SSRH and SHRH, %), total rainfall (SSRA and SHRA, mm), wind speed (SSWS and SHWS, m/s), total sunshine duration (SSSD and SHSD, hr). All climate variables (except SSRA, SHRA, SSSD and SHSD which were calculated as sums over the whole growing stage) were calculated as daily means over the growing stage.

## Results

***Determining the causality of climate variables for the production of whole crop maize***

Six climatic factors were named: Rainfall_SS, Heat-humidity_SS, Temperature_SS, and Night-heat_SH, Temperature_SH and Rainfall_SH. In addition to climatic factors, the production factor consisting of FMY, DMY and TDNY was used as the final response factor. Here, it was necessary to evaluate physiological/ecological evidence to set the path's direction between factors. There was no doubt in setting the direction of climatic factors from before to after because of the time series feature. The path between changes in temperature leading to changes in rainfall can be explained through a long-term mechanism which starts with a temperature rise, and is followed by atmospheric and soil surface moisture evaporation, moisture condensation in the atmosphere, and ends with rainfall (Lydolph et al., 1985). On the other hand, the path between changes in rainfall leading to changes in temperature can be illustrated by controlling the divide between the sensible and latent heat fluxes over a relatively short period of time (Huang and van den Dool, 1993). Therefore, in this study, daily meteorological information was used and concluded that the path from changes in rainfall to changes in temperature was appropriate. Furthermore, for winter forage crops, the cause-and-effect relationship between temperature and precipitation in the causality network was constructed following the path of changes in rainfall to changes in temperature (Kim et al., 2014; Kim et al., 2016; Kim et al., 2019; Kim and Sung, 2019; Kim et al., 2020). Finally, for the stress factors within each stage, the path was explored under the condition of no distortion to other factors.

As a result, the structure for the causality of climate variables affecting WCM production was established as shown in Figure 1. There were three key cause-and-effect relationships: The first was the direct effect of climatic factors on the production of WCM (red-colored). The paths of Temperature_SS, Temperature_SH and Heat-humidity_SS had effects on WCM production ($p < 0.05$). In the case of the insignificant paths (red-colored dash line), the impact of Night-heat_SH on WCM production was not serious because SHLT in Korea was in range of 15.15–21.15°C, it was not at the level to inhibit the growth of WCM. Here, the night temperatures of 70–80°F (21.11–26.67°C) can affect the yield potential of WCM (Peters et al., 1971).

Meanwhile, in the case of Rainfall_SS and Rainfall_SH, the indirect path affected WCM production through two or more paths, while their direct path was not affected. The second key cause-and-effect relationship was the indirect effect of different pathways within the growth stage (green colored). Regardless of the growth stage, rainfall only affected production in connection with the path of temperature, not direct path. Therefore, it was hypothesized that the rainfall does not directly affect production, but rather affects production through a certain temperature. The final key cause-and-effect relationship was the seasonal effects between the SS and SH stages on the longitudinal structure for temperature and rainfall related climatic factors (blue colored). Thus, the effects of the different temperature and rainfall related factors during the SS stage could be categorized into direct and indirect seasonal effects.

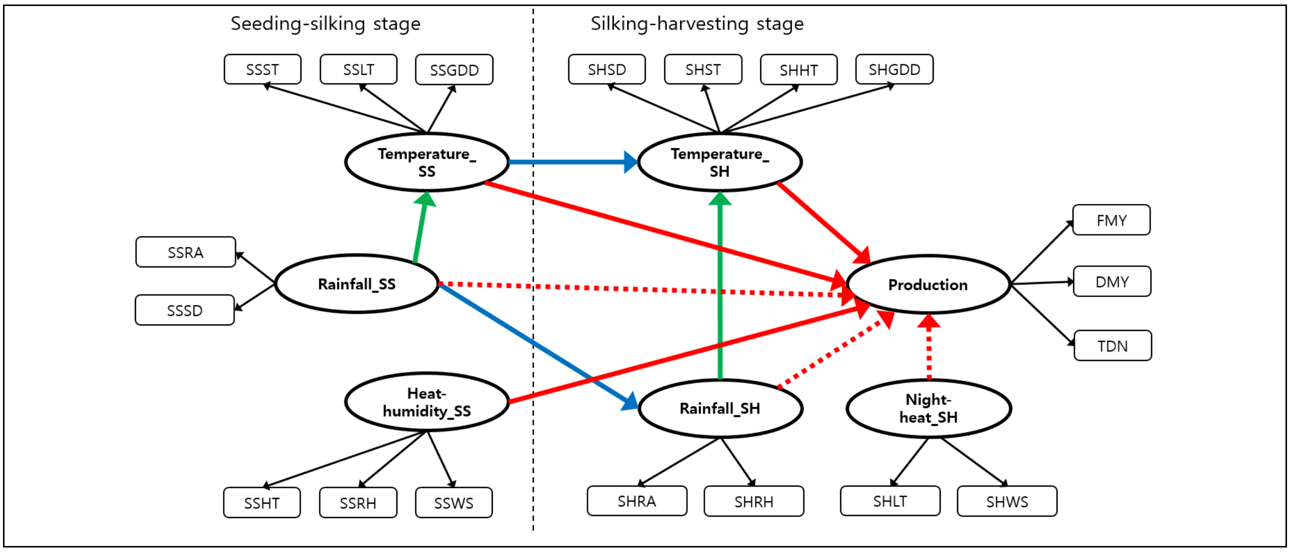


Figure 1. Path diagram for causality of climatic factors affecting production of whole crop maize silage based on before and after silking stage: direct effect on production (red colored), indirect effect (green colored), longitudinal effect (blue colored), solid line ($p < 0.05$), dash line ($p > 0.05$)

FMY: fresh matter yield, DMY: dry matter yield, TDNY: total digestible nutrients yield, SSGDD: seeding-silking growing degree days, SSHT: seeding-silking high temperature, SSLT: seeding-silking low temperature, SSST: seeding-silking soil surface temperature, SSRH seeding-silking relative humidity, SSRA: seeding-silking rainfall amount, SSWS: seeding-silking wind speed, SSSD: seeding-silking sunshine duration, SHGDD: silking-harvesting growing degree days, SHHT: silking-harvesting high temperature, SHST: silking-harvesting soil surface temperature, SHRH: silking-harvesting relative humidity, SHRA: silking-harvesting rainfall amount, SHSD: silking-harvesting sunshine duration

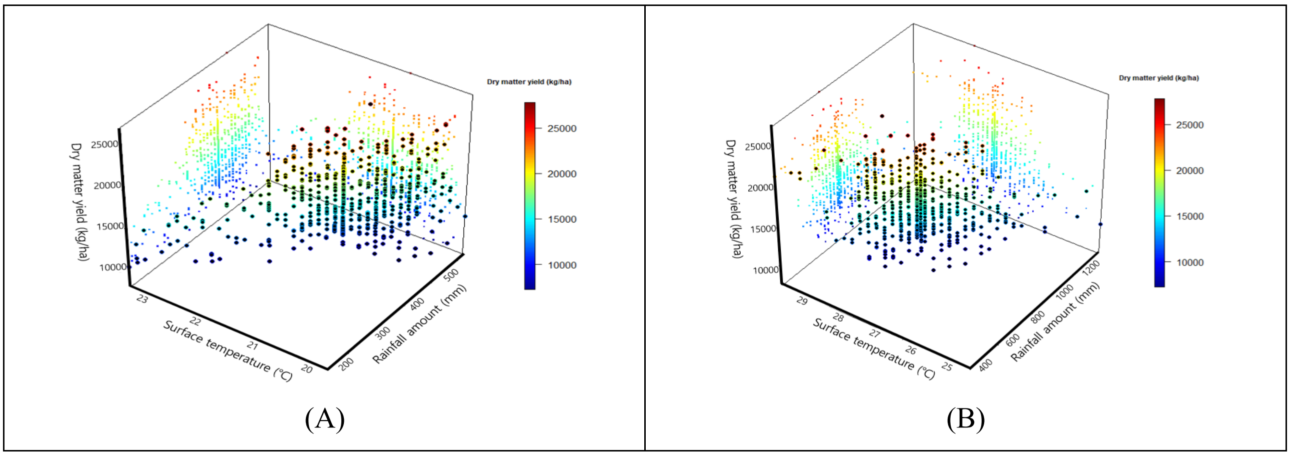


Figure 2. Scatter plots for soil surface temperature and rainfall amount affecting dry matter yield of whole crop maize silage: (A) seeding-silking stage, (B) silking-harvesting stage

***Major causality of climate variables before and after the silking stage***

During the SS stage, high DMY occurred when SSST was less than 22 °C and SSRA was over 300 mm (Figure 2A). This implies that the indirect effect of SSRA occurred through a certain range of SSST (20–22 °C) based on the structure of SEM in this study. Furthermore, within this range of SSST, the variation in SSRA was larger. During the SH stage, the high DMY occurred when SHST was in the 26.5–29.7 °C region and SHRA was less than 900 mm (Figure 2B), which indicates that the indirect effect of SHRA being below 900 mm led to higher DMY when SHST was also higher. According to Willis et al. (1957), the optimum soil temperature was 23.89 °C at a depth of 10.16 cm for WCM growth in central IOWA (40°36'N–43°30'N). Therefore, SSST was a normal level for the growth and development of WCM, whilst SHST was higher. However, while SHST was somewhat higher, it was not at a level that would be concerning for growth as it was still less than the maximum temperature (30 °C) of growing degree days for WCM. In the case of SSRA and SHRA, the appropriate rainfall amount for the growth and development of WCM was 450–600 mm. Furthermore, rainfall that can cause soil erosion is more of a problem when over 200 mm of concentrated rain falls in less than 3 months compared to over 1,000 mm of rain falling over a 12 month period, even when assuming the same amount of monthly rainfall. In this study, areas with either low rainfall in the SS stage or excessive rainfall in the SH stage were found to have low DMY with small variations. In the late 21st century, annual rainfall is expected to increase by 30% in the Korean Peninsula; therefore, there is a concern that production damage of summer crops will gradually increase due to excessive rainfall during the SH stage with overlapping the Changma season.

## Discussion [Conclusions/Implications]

In this study, the causality of climate variables before and after the silking stage was assessed for the production of WCM silage using SEM which contained various cause-and-effect relationships. This study noted three key factors: the seasonal effect before and after the silking stage, the indirect effect of rainfall based on appropriate temperature, and the damage caused by heat-humidity before the silking stage. Furthermore, it has been found that only a certain range of rainfall affected WCM production when the temperature was appropriate before and after or within the silking stage for the major causality.

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