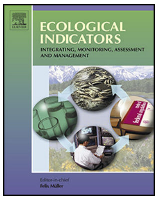
Ecological Indicators 61 (2016) 149–158

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Short communication

Growing degree days – Ecosystem indicator for changing diurnal temperatures and their impact on corn growth stages in Kansas

Aavudai Anandhi[a,b,*]

[a] Department of Agronomy, Kansas State University, Manhattan, KS 66506, USA
[b] Currently with Biological and Agricultural Systems Engineering (BASE), College of Agriculture and Food Science, Florida Agricultural & Mechanical University, Tallahassee, FL 32307, USA

ARTICLE INFO

Article history:
Received 7 August 2014
Received in revised form 22 July 2015
Accepted 13 August 2015
Available online 1 December 2015

Keywords:
Corn growth stages: emergence, tassel initiation, tassel emergence, silking, dough stage, dent stage, and physiological maturity
Kansas centennial stations
Heat units
Growing degree days
Climate change
Adaptation

ABSTRACT

Understanding how climate change will affect plant phenology (shifts in the timing of plant activity) is central to many ecological and biogeochemical studies. This aspect of plant ecology often has been overlooked, but addressing the consequences of climate change for adaptive/mitigative management is now high on the list of priorities for funding agencies. This study is innovative because it uses growing degree days (GDD), which has existed since the 1730s, as an ecosystem indicator to study changing diurnal temperatures; their effects on different plant growth stages in the last century; and as a basis for development of future adaptive management strategies. Our results show the most recent time period (1980–2009) had the earliest emergence and the least variability among stations in the day at which the crop stage occurred for most stages except emergence and physiological maturity. 100 year linear trends in the stations indicated all seven crop stages except tassel initiation occurred earlier by one day per decade during the study period. The number of stations with significant decreases varied from 11 to 17 stations out of 23 stations in Kansas. Tassel initiation stage occurred later by one day per decade during the study period. The most recent time period (1980–2009) had the highest variability among stations and 30 year time periods. The variability in trends is higher in western Kansas when compared to eastern Kansas. This knowledge has transformative potential to improve our understanding of the occurrence and duration of the different plant growth stages, add local precision to earlier findings for changes in overall GDD that encompassed larger areas, and help explain the differences in trends from some earlier studies. These shifts in the phenology of agricultural plants as a result of climate change have implications on food production increases required to feed the growing population.

Published by Elsevier Ltd.

1. Introduction

Measuring “heat units” started with the concept that growth and development of plants are related to temperature and do not occur beyond a threshold temperature (Esparza et al., 2007), an idea that has been used in studies relating to growth and development during the growing season (Kadioğlu and Şaylan, 2001). The “heat units approach” or “remainder index method” has been used since about 1730 (Wang, 1960) and is known by a number of expressions, including “thermal time”, “degree-days”, “heat units”, “growth units”, or “growing degree days” (Feng and Hu, 2004; Wang, 1960). Growing degree days (GDD) is used widely in many applications: (1) as a phenoclimatic measurement to represent changes in temperature that are relevant to different phases of plant development (Cleland et al., 2007); (2) as a hybrid maturity descriptor by the seed industry to help make late planting decisions (e.g., choosing early maturity varieties) because delayed planting and replanting shorten the effective growing season and GDD can characterize the growing season (Nielsen et al., 2002; Thomison and Nielson, 2002); (3) as a measurement to study the effects of planting dates on crop yield (Bollero et al., 1996); (4) as an indicator useful in the practice of sustainable management and development of forests and agriculture through plant functions such as evapotranspiration, photosynthesis, plant respiration, and plant water and nutrient movement (Hassan et al., 2007); (5) as a way to predict N release from crop residues and other amendments (Griffin and Honeycutt, 2000); and (6) as an explanation of seasonal variation in the linear increase of the harvest index, which increases crop yield (Lu et al., 2001). Variations in GDD also can be an important indicator of climatic change effects on plants that may not be represented in mean conditions.

As temperatures increase during the next century, shifts may occur in crop production areas because temperatures will no longer

---

* Tel.: +1 8504125000; fax: +1 850 412 5004.
E-mail address: anandhi@famu.edu

http://dx.doi.org/10.1016/j.ecolind.2015.08.023
1470-160X/Published by Elsevier Ltd.

occur within the range or during the critical time period for optimal growth and yield of grain or fruit (Walthall, 2012). The challenge of increasing food production to meet the needs of the increasing population has become more urgent than ever (Tscharntke et al., 2012) even as climate change variations and events threaten both land and water resources (Horlings and Marsden, 2011). In addition, numerous studies examining frost dates and growing season length have found changes that are consistent with climate warming (Anandhi et al., 2013a,b). Increasing temperature could significantly alter plant phenology because temperature influences the timing of development, both alone and through interactions with other factors (e.g., photoperiod). These are often-overlooked aspects of plant ecology (Cleland et al., 2007) and have important implications for agricultural production.

Temperature changes present unprecedented challenges to the adaptive capacity of agriculture by influencing crop distribution and production and by increasing the economic and environmental risks associated with a multitude of agricultural systems (Walthall, 2012). Many adaptation programs and strategies do not yet sufficiently connect with regional and local planning and management programs because much academic research is not being conducted with the objective of meeting specific decision-makers' information needs (Bolson et al., 2013; Moser and Luers, 2008). Improving the link between climate impacts and adaptation research and public and private planning and management decisions is a critical challenge in supporting climate change adaptation (Mastrandrea et al., 2010). GDD can be considered a climate impact index that helps translate academic climate change research and makes it useful in making planning and management decisions.

Detailed information on geographical and temporal variations of GDD can be beneficial for updating management decisions and recommendations (e.g., timing of sowing and harvesting; effective timing for irrigation, fertilizer, and pesticides) for local and regional agricultural production, supporting agricultural research and education (e.g., phenology of hybrid varieties), and providing compelling evidence that species and ecosystems are being influenced by global environmental change (e.g., shifts in the timing of plant activity). A few studies have examined variations in GDD for larger regions encompassing Kansas, but no studies have compared the 100 year trends in GDD for different time periods and crop growth stages in Kansas. Therefore, the main objective of this study was to examine 100 year and 30 year variation and trends in Kansas GDD for seven crop growth stages of corn in four different time periods using 23 Centennial Weather Stations. The secondary objective of this study was using GDD to translate academic climate change research to information that can help make management decisions in food production systems.

2. Definition of GDD

The canonical form of calculating *GDD* is provided in Eq. (1).

$$GDD = \frac{[T_{\max} + T_{\min}]}{2} - T_{base} \tag{1}$$

$$T_{\max} = \begin{cases} T_{\max} & 30\,^{\circ}\mathrm{C} > T_{\max} > T_{base} \\ 30\,^{\circ}\mathrm{C} & T_{\max} \geq 30\,^{\circ}\mathrm{C} \\ T_{base} & T_{\max} \leq T_{base} \end{cases} \tag{2}$$

$$T_{\min} = \begin{cases} T_{\min} & 30\,^{\circ}\mathrm{C} > T_{\min} > T_{base} \\ 30\,^{\circ}\mathrm{C} & T_{\min} \geq 30\,^{\circ}\mathrm{C} \\ T_{base} & T_{\min} \leq T_{base} \end{cases} \tag{3}$$

where T_{max} and T_{min} are daily maximum and minimum air temperature in degrees Centigrade and T_{base} is the base threshold temperature in degrees below which the process of growth does not progress. T_{base} varies among species and possibly cultivars and likely varies with growth stage being considered. In this study, T_{base} is 10 °C (50 °F). 30 °C (86 °F) is the upper threshold temperature because plant roots have greater difficulty taking in water fast enough to keep the plant growing at full speed (Duncan et al., 2010). More details such as modifications of Eq. (1) and implications of the various definitions can be found in McMaster and Wilhelm (1997). This study assumes that the GDD required to complete a given growth stage is constant for a hybrid regardless of the temperatures experienced; however, GDD have been found to vary with soil temperature (Bollero et al., 1996).

Eq. (1) describes the heat energy received by the crop over a given time period by integrating the area under the diurnal temperature curve, summing the daily heat energy over an interval of time and then relating the accumulation of heat energy to progress in development or growth processes (McMaster and Wilhelm, 1997).

3. Data and statistical techniques used in the study

3.1. Study region and data

Kansas is the study region. It is important to study Kansas because it lies between 37° and 47° N latitude, where Manabe and Wetherald (1980) have predicted that, due to climate change an increase in CO_2, a decrease in precipitation, an increase in evaporation, and a decrease in excess of precipitation over evaporation will occur. Further, the corn production regions in Kansas largely overlie the High Plains (Ogallala) aquifer. This region is considered one of the most productive agricultural regions and are referred to as the "breadbasket of the world." (Sanderson and Frey, 2014) or the "grain basket of United States" (Scanlon et al., 2012). The Kansas portion in High Plains aquifer supports the congressional district with one of the highest market value for agriculture in the nation; and declining water levels in the aquifer would cut agricultural production (Steward et al., 2013). Exposure of the agricultural production in this region to changing climate such as longer growing season and changing developmental stage can further increase the vulnerability of ecological and hydrological systems in this region. This creates a need for adapting the corn production to utilize the benefits of changes while reducing the adverse impacts of change.

Daily maximum ($T_{\max}$) and minimum air temperature ($T_{\min}$) data were downloaded from the High Plains Regional Climate Center's website for 23 Centennial Weather Stations across Kansas. The locations and periods of record are provided in Fig. 1a and Table 1. The records began from 1890 to 1908; consequently, the start dates of the records are different, but the end dates are the same (2009). The records were selected to cover non-overlapping 30-year timespans backward from 2009. The four time periods were through 1919, 1920–1949, 1950–1979, and 1980–2009. Weather stations were selected for their long-term quality, based on criteria such as consistent observation times, low potential for heat-island bias (Robeson, 2002). The other quality checks were: statistical outliers were identified and checked against original records; so was the minimum temperature less than maximum temperature.

3.2. Steps and statistical techniques used

The steps involved in estimating GDD are provided in Fig. 1b for the seven growth stages of corn: emergence, tassel initiation, tassel emergence, silking, dough stage, dent stage, and physiological maturity.

Step 1: Calculate GDD: For each station and day of the year, GDD was calculated using Eq. (1) in Centigrade scale using the station's daily $T_{\max}$ and $T_{\min}$.