Weather, Climate, & Agriculture

by Trent Ford and Jim Angel

Introduction

The key atmospheric and land variables that impact crops are solar radiation, air temperature, humidity, precipitation, and soil moisture. The day-to-day variability of these variables can be described as *weather*. Weather extremes at critical periods of crop development or phenology can have dramatic influences on productivity and yield. The long-term average temperature and humidity, total solar radiation and precipitation, and average soil moisture over a crop's growing season can be described as the *climate*. It is the climate that, in the absence of weather extremes, determines the realized yields for a given region. Additionally, Illinois' climate has changed over the past century and models project continued change to the end of this century. These changes have had tangible impacts on agriculture.

This chapter addresses how plants respond to these variables, how they vary over the season and across Illinois, to what extent they can be predicted, and how they have changed over the past century.

Crop Response to Weather Variables

The response of crops to the different weather variables is quite complex and difficult to describe. If one of the variables is limiting (for example, temperatures that are too high or too low), then the effects of solar radiation or precipitation do not greatly affect the crop. At the same time, extremes in one variable can amplify the effect of another variable, such as the heightened impact of high temperatures during drought. When none of the variables is limiting, the crop will respond to the variable that is farthest from the optimum for that variable. Describing the physiological response of crops at the field level introduces additional uncertainty in predicting crop yield. Predicting the exact response of crops to the weather and climate is, as a result, an inexact science, and one that contains great uncertainty.

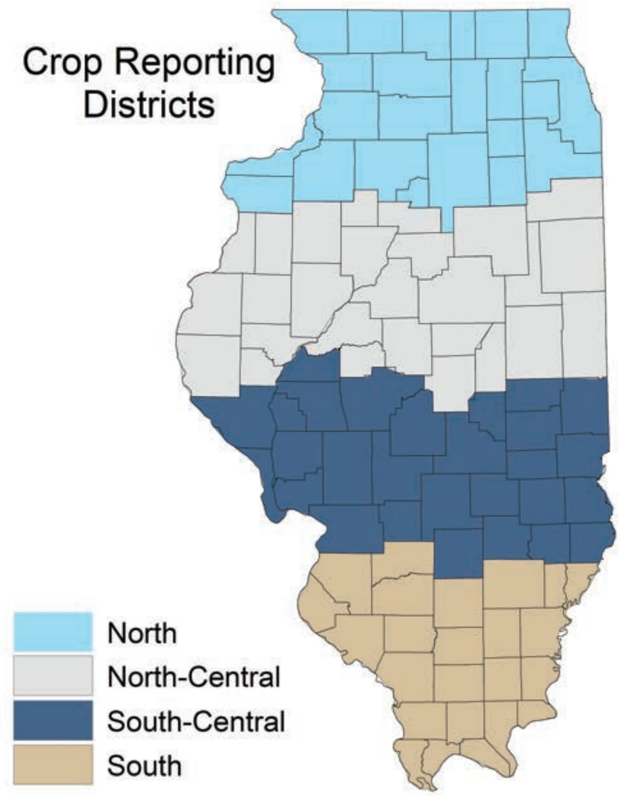

Figure 1.1. Regions used in this chapter.

The information presented in this chapter is based on "normal" weather conditions. Normal is defined by the World Meteorological Organization as a 30-year period updated every decade. The current period is 1991 to 2020. A "normal" year seldom occurs, if ever, because there is always variability of the weather from normal across years and within a year, with some periods being wetter/drier, hotter/colder, sunnier/cloudier than normal. Information in this chapter is presented by four groups of crop reporting districts (CRDs). The north group includes CRDs 1 and 2, the north-central group includes CRDs 3, 4, and 5, the south-central group includes CRDs 6 and 7, and the south group includes CRDs 8 and 9 (Figure 1.1).

Temperature

Other than planting date, temperature is the main variable that determines when a crop will grow. It also determines, along with precipitation and solar radiation,

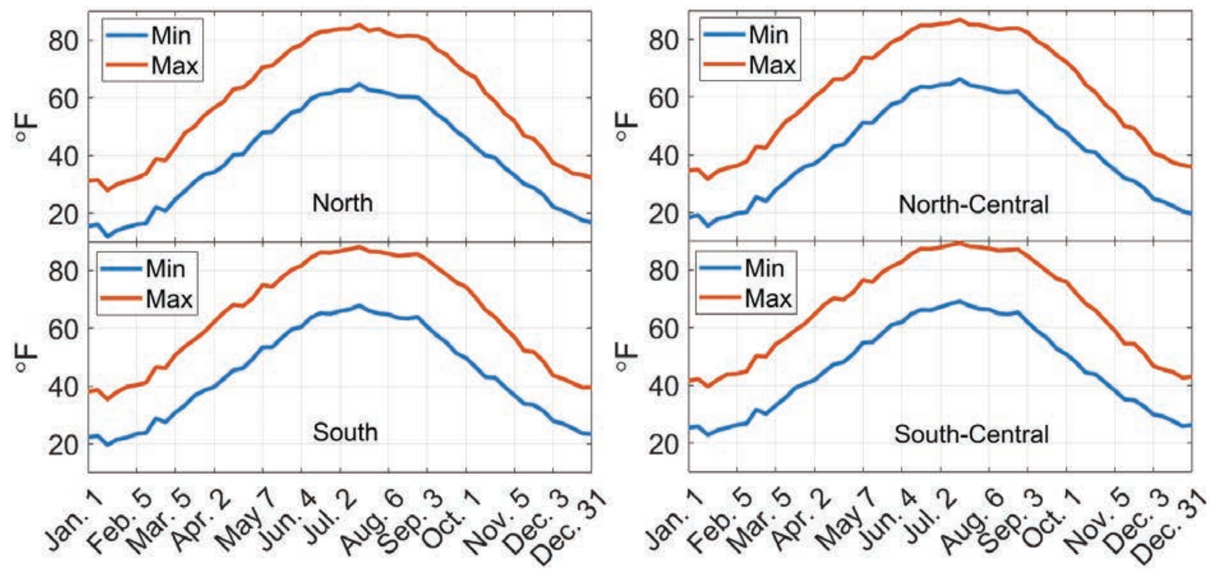

Figure 1.2. Weekly average maximum (red) and minimum (blue) temperatures in each of the four regions. Temperatures represent the 30-year average over the period 1991 to 2020.

how well a crop will grow and how fast it will develop. There are four temperature thresholds, called the cardinal temperatures, that define the growth of a crop: the absolute minimum, the optimum minimum, the absolute maximum, and the optimum maximum. The absolute minimum and maximum temperatures define the coldest and hottest temperatures, respectively, at which a crop will grow. Temperatures between the optimum minimum and maximum define the range of temperature where the crop performs the best. Corn (*Zea mays* L.), for example, has an absolute minimum temperature of 50°F, an optimum minimum of 64°F (18°C), an absolute maximum of 117°F and an optimum maximum of 91°F. Corn is an example of a C4 crop, which originates from a tropical environment. C4 crops, which also include Miscanthus (*Miscanthus x giganteus*) and sorghum (*Sorghum bicolor*), have absolute minimum temperatures ranging from 45 to 50°F optimum minimums from 59 to 81°F, absolute maximums from 104 to 117°F, and optimum maximums from 91 to 104°F. C3 crops, including wheat (*Triticum aestivum*), soybean (*Glycine max*), and alfalfa (*Medicago sativa*), have absolute minimum temperatures ranging from 36 to 41°F, optimum minimums from 59 to 68°F, absolute maximums from 81 to 100°F, and optimum maximums from 73 to 91°F.

These temperature thresholds can be used with Figure 1.2 to identify the weeks when the weekly mean maximum and minimum temperatures are within the absolute and optimum temperature ranges. Using corn as an example, the weekly mean minimum temperature is at or above the minimum optimum temperature from June 11 through September 3 in the northern two crop reporting districts (CRDs 1 and 2) and from May 28 through September 10 in the southern two crop reporting districts (CRDs 8 and 9). The north-central region represented by crop reporting districts 3, 4, and 5, experiences weekly mean minimum temperatures within the optimum temperature range approximately one week earlier in the spring and one week later in the fall than the north region, and one week later in the spring and one week earlier in the fall than the south-central region, represented by crop reporting districts 6 and 7. During these periods, the temperature conditions are generally considered to be optimum for corn growth and development.

Growing Degree Days: Research has shown that crop development—the time from planting to flowering and/or maturity—is more closely correlated with temperature than with the number of days after planting. Growing degree days (GDDs), are used to relate temperature to crop development. GDDs are accumulated when the

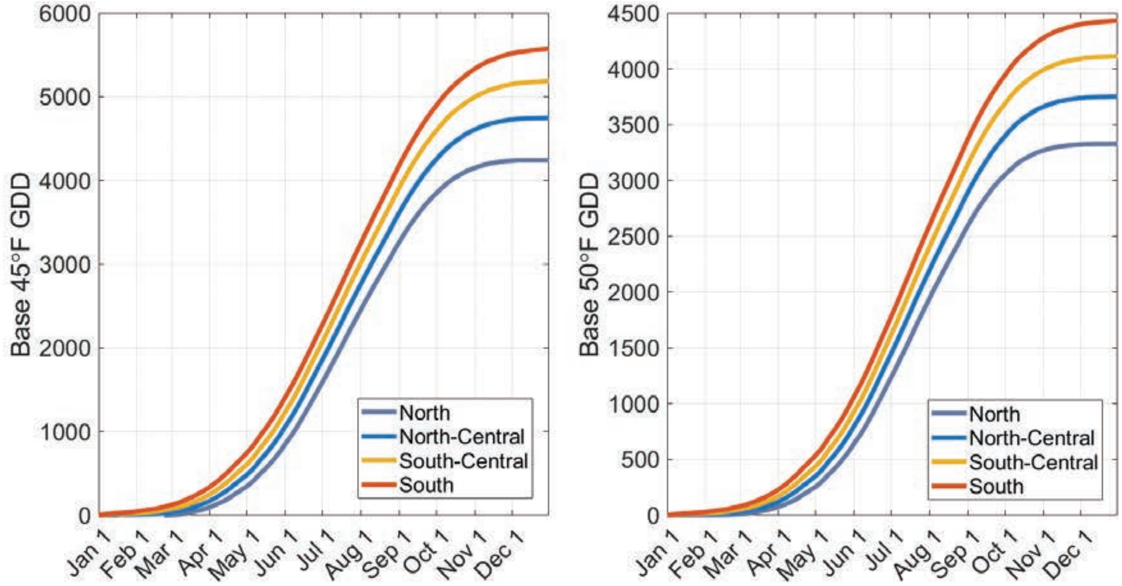

Figure 1.3. Accumulated growing degree units (left) base 45 and (right) base 50 for each region. Average GDD accumulation is calculated over the period 1991 to 2020.

mean daily temperature exceeds a threshold identified for a crop. When calculating base 50°F GDDs, a day's maximum temperature is set to 86°F if its maximum temperature exceeds 86°F, and its minimum temperature is set to 50°F if its minimum temperature is less than 50°F. If the mean daily temperature for a day is 51°F, one GDD is accumulated. If the next day's mean temperature is 55°F, then 5 GDDs will accumulate for the day and 6 GDDs will have accumulated for the two-day period. The basis equation for computing accumulated GDDs is:

$$GDD = \sum_{Day=1}^{n} \frac{T_{MAX} + T_{MIN}}{2} - T_b \qquad (1)$$

where is the maximum daily temperature, is the minimum daily temperature, and is the threshold temperature.

The annual accumulated GDDs are greatest in the southern region of Illinois (Figure 1.3). The annual accumulation of GDDs is 1,200 more in the south than in the north for a base 45°F. For the modified 50°F accumulation, the south accumulates approximately 1,100 more than the north. This greater accumulation in the south compared to the more northerly regions of Illinois is the result of an earlier start to accumulation in the spring, a later end in the fall, and a pace slightly faster during the summer, when the south accumulates approximately 40 more GDDs per week than the north. The greater accumulation in the south provides the potential for growing crops that require a longer growing season to mature than in the north.

Average annual temperature in Illinois has increased by approximately 1°F over the past century, with much of the warming in climatological winter and spring. This long-term warming has resulted in an overall increase in GDD accumulation during the growing season in all parts of Illinois (Figure 1.4). Total growing season (May to September) GDD accumulation has increased by 3 to 4 GDDs per season over the past 70 years in Illinois, with slightly larger trends in the south region. The result of

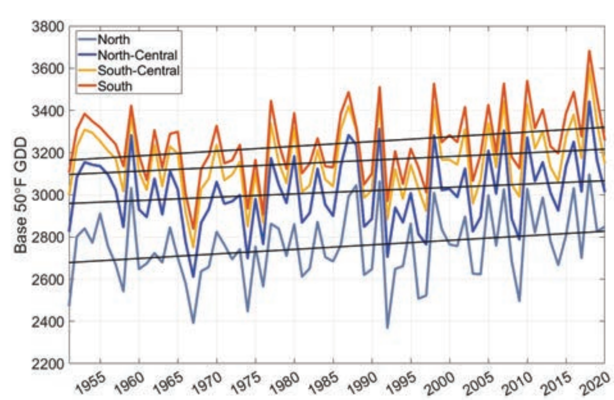

Figure 1.4. May to September base 50 GDD in each region between 1951 and 2020. Trends are shown by the black lines and are calculated over the 70-year record.

this change is that each of the four regions accumulates approximately 200 to 300 additional GDDs per season in recent years compared to the 1950s. These changes illustrate an expansion of the growing season in Illinois due to climate change.

Temperature Stress Crops experience stress from both heat and cold. Heat stress mostly occurs in the summer, while cold stress occurs in the spring and fall, usually when crops are being established or maturing. Cold stress is not a serious problem for most agronomic crops in Illinois; heat stress is more likely, especially in summers when temperatures approach or exceed 90°F. When temperature exceeds a crop's optimum maximum, the crop experiences heat stress.

Heat stress affects plants because as temperature increases, respiratory reaction rates speed up, using more of the photosynthetic compounds manufactured in a day. Also, with elevated maximum temperature, especially temperatures that exceed 100°F (38°C), plants require more water to maintain optimum water content in their tissues. If the soil cannot meet the additional water requirement, heat stress is compounded by water stress. Most crops in Illinois can withstand temperatures below 95°F (35°C) unless they are accompanied with drought stress, so heat stress usually results in only minor yield losses.

High nighttime temperatures can also have detrimental impacts on crop development and yield. Specifically, nighttime temperatures above 75°F can result in wasteful respiration and a lower net amount of dry matter accumulation in plants. The result is less sugar retained to fill kernels or seeds. This effect is particularly large on corn, although soybean plants are also susceptible to very high nighttime temperatures. All four regions of the state have experienced increased frequency of very warm nights, those in which the daily minimum temperature remains above 75°F, over the historical period 1951 to 2020 (Fig. 1.5).

Over the same period, none of the regions has experienced a significant change in the frequency of very hot days, those in which the daily maximum temperature reaches above 95°F.

Soil Temperature Soil temperatures in the autumn determine when ammonium nitrogen fertilizer may be applied without excessive nitrification occurring during the autumn and winter. With soil temperatures at a depth of 4 inches below 50°F, the rate of nitrification is reduced, but the process becomes negligible only when soil temperatures are below 32°F. The maps in Figure 1.6 show the last day in the fall that 4-inch soil temperatures are above 50°F and 60°F. Normally soil temperatures throughout the state are consistently

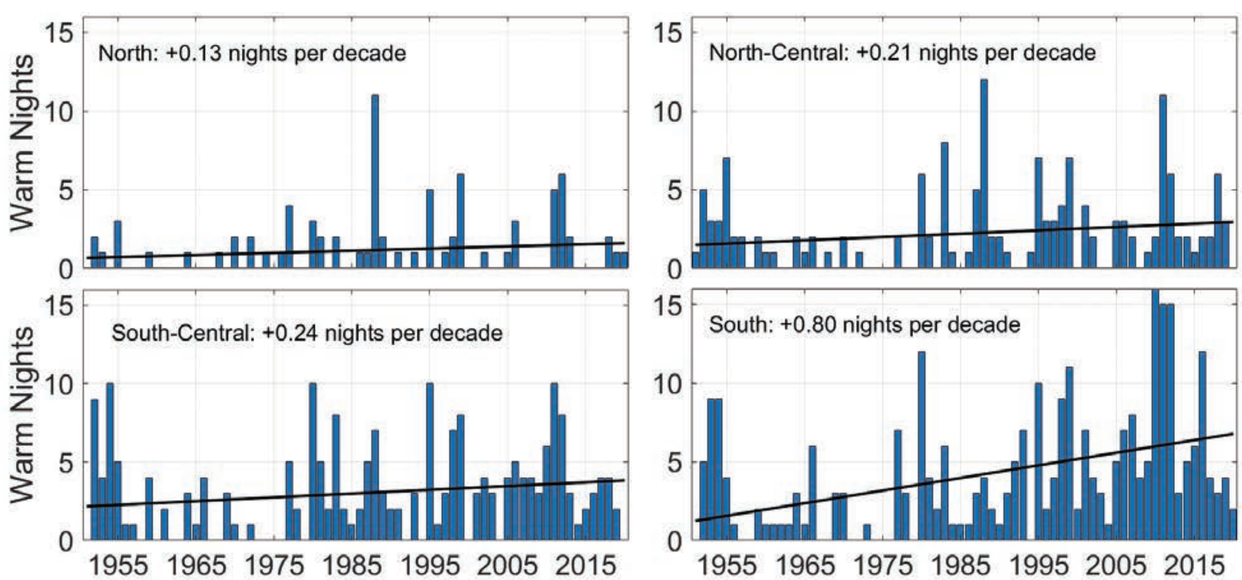

Figure 1.5. Annual frequency of very warm nights in each of the state's four regions. The black lines indicate the frequency trends over the 70 year period.

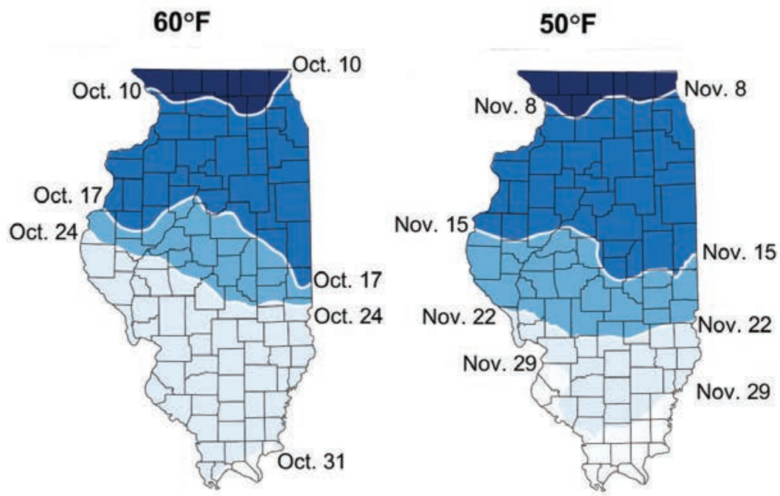

Figure 1.6. The average last fall dates when 4" soil temperatures were estimated to be above 60F (left) and 50F (right). Averages calculated for the period 1991-2020.

below 60°F by the end of October and below 50°F by the end of November. Maps showing the dates when soil temperatures fall below 60°F are included as a guide for estimating when anhydrous ammonia applications with a nitrification inhibitor may begin. Soil temperatures can be estimated by computing the average of the mean air temperature for the preceding 7 days. These estimates tend to underestimate soil temperatures by 3 to 4°F in the autumn. Therefore, the maps in Figure 1.6 indicate the last day the 7-day average air temperature was above 47°F to account for this difference.

Growing Season Length: The growing season is defined as the period between the last spring frost and the first fall frost. A frost will generally occur when the minimum temperature is less than or equal to 32°F. Most annual crops are planted after the major risk of frost or freeze has passed. However, late frosts – particularly very late frosts – can damage both annual and perennial crops during the spring. Frosts or freezes with temperatures less than 30°F result in major damage to crops in the spring. Mean dates of last spring frosts are as early as April 1 in southern Illinois and as late as April 22 in northern Illinois (Figure 1.7). In 1 out of every 10 years, the last spring frost can occur as early as March 18 in southern Illinois and as early as April 15 in northern Illinois. In nine years out of 10 the last spring frost occurs as late as April 57 in southern Illinois, and as late as May 13 in northern Illinois.

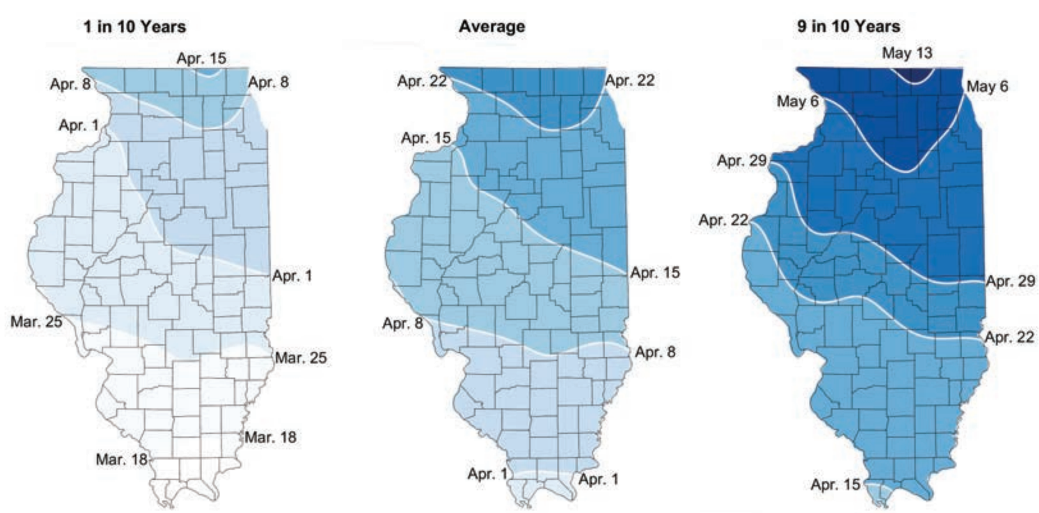

Figure 1.7. Last spring freeze dates for 1 in 10 years (left), 9 in 10 years (right), and the 30-year average (middle). Values are calculated over the period 1991 to 2020.

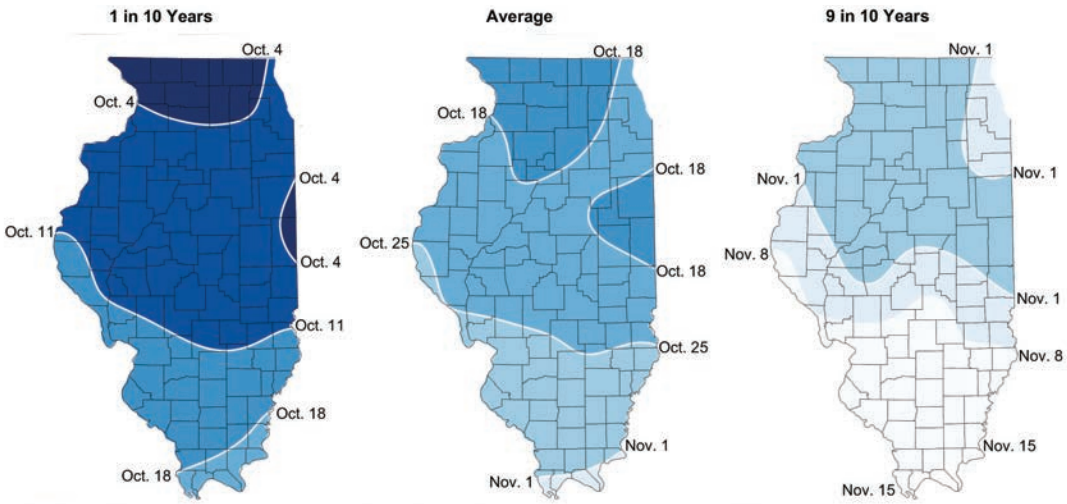

Figure 1.8. First fall freeze dates for 9 in 10 years (left), 1 in 10 years (right), and the 30-year average (middle). Values are calculated over the period 1991 to 2020.

The average dates of first fall frosts range from October 18 in northern Illinois to November 1 in southern Illinois (Figure 1.8). In 1 out of 10 years, the first fall frost occurs by October 4 in northern Illinois and October 18 in southern Illinois. In 9 out of 10 years, the first frost occurs before or on November 1 in northern Illinois and November 15 in southern Illinois.

These dates mean that the normal growing season is generally less than 180 days in northern Illinois and more than 200 days in southern Illinois (Figure 1.9). In north-central Illinois, which includes crop reporting districts 3, 4, and 5, the growing season is approximately 190 days.

Temperature Inversions: Air temperature typically decreases with height in the troposphere, the layer of the atmosphere in which we live. However, in certain situations, temperature may increase with height, and this is known as a temperature inversion. Most inversions occur very close to the ground during the overnight hours when there is little to no cloud cover and very little wind. These conditions cause pooling of cooler, denser air near the surface and maintain warmer air above. Temperature inversions occur in all four seasons but are particularly problematic for agriculture in late spring and early summer because they increase the risk of pesticide drift. The strong atmospheric stability associated with inversions allows chemicals to be transported over much larger areas than the intended application site, in some cases settling in neighboring fields and causing unintended crop and property damage.

Weather monitoring networks in several Midwest states, including the Water and Atmospheric Resources Monitoring (WARM) Program in Illinois, have begun monitoring temperature and wind speed at several heights above the surface to provide warning for temperature inversions. However, because inversions can be very local in scale, applicators are strongly encouraged to be aware of weather conditions, in particular wind speed and direction both at shoulder height and boom height, when planning to spray.

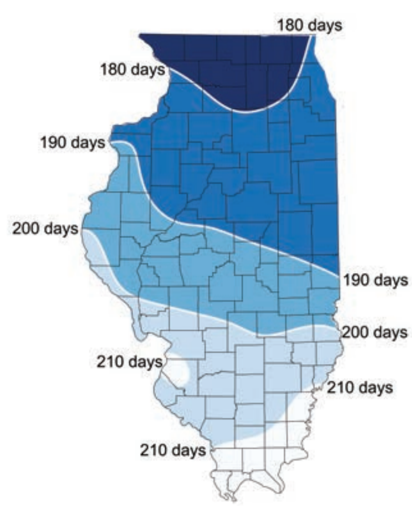

Fig. 1.9. Average growing season length (days), measured as the time between the last spring freeze and first fall freeze. Averages are computed for the period 1991 to 2020.

Precipitation

The type, timing, and amount of precipitation received during the year play critical roles in crop productivity. Precipitation types include unfrozen (rain and freezing rain) and frozen (snow, sleet, and hail). Snow and sleet occur in the winter and hail in the warmer seasons. In the winter, frozen precipitation is less efficient than unfrozen in recharging the soil profile due to its accumulating on the soil surface, which can be frozen. As the snow melts on a frozen soil surface, the water tends to run off rather than infiltrate into the soil. Also, snow on the surface will be transformed directly into water vapor (i.e., sublimate) and be carried away from the soil surface. Sublimation occurs even with air temperatures below freezing. Snow may also blow off fields and into ditches and fence rows, further limiting its contribution to soil moisture in the field.

Rain is generally more efficient in recharging the soil profile and thus is more available for crops. The efficiency of rain in recharging the soil depends on the rate or intensity with which the rain falls. Rain showers or storms that fall at rates greater than 0.5 inches per hour are less efficient than lighter showers because the water forms ponds on the surface and runs off the fields into ditches and rivers. Runoff also carries with it topsoil and nutrients that are applied to the field.

The timing of precipitation is critical to crop growth. In the period from harvest to planting, referred to as the fallow season, recharge of the soil profile occurs. In Illinois, there is usually enough precipitation to recharge the soil profile in January of the year following the harvest. In those years when the soil profile is not recharged by January, rainfall during February, March, and April is usually adequate to recharge the soil profile. If the soil profile is not sufficiently recharged during the fallow season, it can create conditions that are more conducive to drought in the following growing season because of a greater likelihood of soil water deficit during critical crop growth stages.

Timing of Precipitation: The timing of rainfall while crops are growing is critical. During seed germination and stand establishment, either too much or too little rain can influence yields. Too much rain, especially with cool temperatures, can result in seed diseases, causing poor stands, or can saturate the soil, causing poor soil aeration and poor germination and stands. Dry soils during germination and stand establishment can result in either poor seed germination or weak and small plants that may not withstand dry weather during the early growth of the crop, causing smaller plant leaf area. For corn, the critical time during the early growth lasts for approximately 30 days, from planting to tassel initiation, when the corn leaves are being initiated and beginning to grow.

During the rapid vegetative growth state, too much rain can result in a smaller shoot-to-root ratio and the establishment of shallow roots. When this happens, the crop is more susceptible to dry spells during the hot months of July and August when the crop is flowering and establishing harvestable grain on ears of corn or pods on soybean plants. A dry period after the crop stand has been established will result in a greater shoot-to-root ratio, with roots growing deeper into the soil profile and allowing the plant to use more of the water stored in the soil. After a dry spell, if adequate rain to recharge the soil is received in the 2 weeks before corn tasseling and pollination, the effect of the dry spell will be minimized. Rainfall during the week or two before the start of flowering in the soybean crop will also reduce the effect of a dry spell during the pure vegetative growth stage.

Rainfall of 1 to 2 inches in the 2 weeks following corn pollination will generally result in the highest yields, especially if the period of pollination had adequate soil moisture. The period from corn pollination to maturity is about 60 days. If soil moisture is near normal to wetter than normal, a dry spell from day 14 to day 60 after pollination will have a small influence on final corn yield. However, if no rain were to occur during those 46 days, final yield and crop quality would be reduced.

Because the soybean crop continues to flower and fill pods form the start of flowering to almost the beginning of maturity, soybean requires adequate rainfall throughout the months of July and August for best yields. Failure to

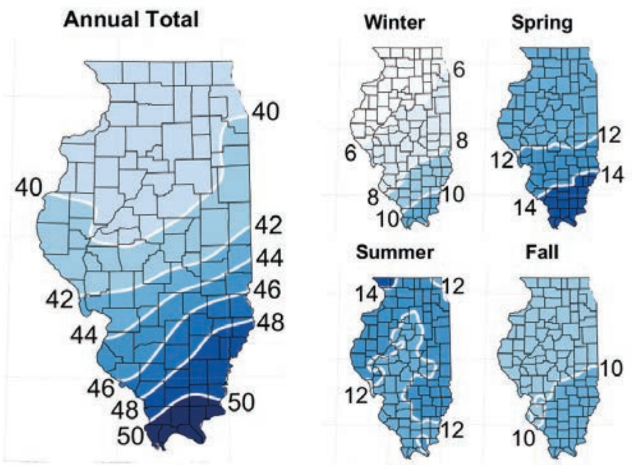

Figure 1.10. Average total precipitation for (left) the calendar year and (right) each season. Totals are in inches, and averages are calculated for the period 1991-2020.

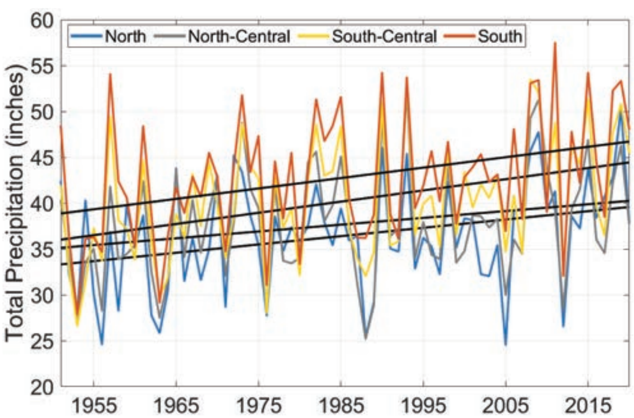

Figure 1.11. Annual total precipitation in each region between 1951 and 2020, in inches. Trends are shown by the black lines and are calculated over the 70-year record.

receive adequate rainfall during flowering and pod fill will result in fewer flowers and pods on the plants.

Generally, annual rainfall exceeds the water requirement of Illinois crops. Mean annual rainfall is greatest in southern Illinois (Figure 1.10), between 46 and 50 inches. Annual total precipitation in the northern half of the state is between 38 and 42 inches. However, there is a south-north gradient: seasonally, there is more precipitation in the south-central region during winter, spring, and fall than in the north-central and northern regions. Conversely, summer precipitation is greater in the north (12 inches) and north-central regions than in the south. Winter is the driest season, between 4 and 6 inches of precipitation in the north and 10 inches in the south. Spring is the wettest season in the south, with more than 14 inches of precipitation, whereas summer is the wettest season in the north, with 12 inches of rain.

Changes in Precipitation: The increasing trend in temperatures across Illinois over the past century has been accompanied by similar increases in the amount of water vapor or humidity in the air. This is often represented by saturated vapor pressure, or the estimated amount of pressure exerted by humidity in the air when the air is saturated. Given the right environmental conditions, higher atmospheric humidity can lead to more precipitation overall and more precipitation intensity. Figure 1.11 shows annual total precipitation has increased in all regions in Illinois over the period 1951 to 2020. Annual precipitation in the north and north-central region have increased by approximately 0.80 inches per decade and by approximately 1.20 inches per decade in the south-central and south regions.

Precipitation intensity has also increased over the past century in Illinois. Although there are numerous ways to measure precipitation intensity, Figure 1.12 shows the 5-year average annual frequency of heavy precipitation days, those in which 2 or more inches of rain fall in a single day, between 1951 and 2020. All four regions have experienced significant increases in heavy precipitation frequency, although the overall heavy precipitation frequency and rate of change in frequency are larger in southern Illinois than in north and north-central Illinois. More intense precipitation increases soil erosion and nutrient runoff, creating water quality issues such as making more conducive environments for harmful algal blooms. Additionally, the runoff ratio, the ratio of precipitation that runs off into streams to the amount that infiltrates into the soil, increases as precipitation intensity increases. Therefore, more intense precipitation reduces soil moisture recharge and can put a region at greater risk for moisture limitations during subsequent dry spells or droughts.

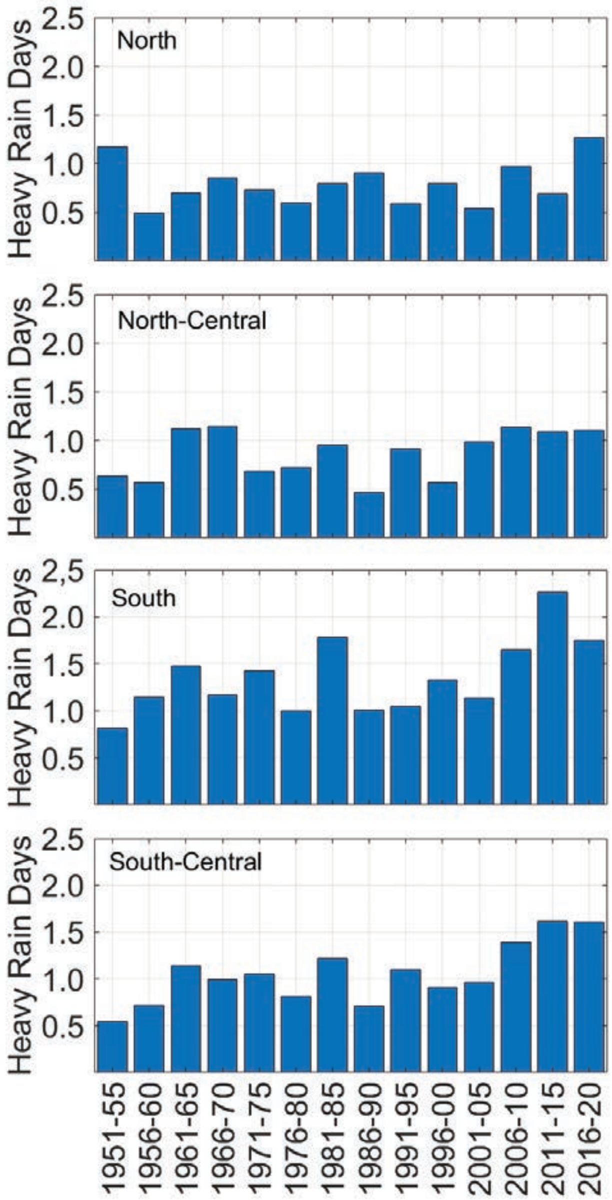

Figure 1.12. Five-year average annual frequency of heavy precipitation days, those in which 2 or more inches of precipitation occur in a single day.

Potential Evapotranspiration

Evapotranspiration is the removal of water from soil by a combination of evaporation from the soil surface and transpiration (loss of water vapor) from plant leaves. Surface evaporation is limited to the top 2 to 4 inches of soil, while transpiration results in removal of water from the soil to a depth equal to the deeper roots.

Potential evapotranspiration is the amount of water that would evaporate from the soil surface and from plants when the soil is at field capacity, which is the amount of water remaining in the soil after it has been saturated and then drained. Soil that is drier than field capacity will experience actual evapotranspiration less than potential evapotranspiration. Actual evapotranspiration will also be less than potential evapotranspiration when plant canopies do not totally cover the soil.

Potential evapotranspiration is greatest in warm, dry years with high temperatures, low humidity, and predominantly clear skies, and is least in cool, wet years with high humidity and cloudy skies. Figure 1.13 shows daily accumulation of potential evapotranspiration at four Water and Atmospheric Resources Monitoring (WARM) program stations in Illinois, one in each of the four regions. Potential evapotranspiration from April through September ranges from about 35 inches in dry years to about 28 inches in wet years. During wet years, actual evapotranspiration will approximately equal potential evapotranspiration. In dry years, actual evapotranspiration will be less than potential evapotranspiration. During the growing season, the normal total monthly evapotranspiration is least in September, between 3 and 4 inches, and greatest in June and July, between 5 and 6 inches. Potential evapotranspiration is highest in June and July because the sun is highest in the sky during those months, and more solar radiation is received during each day because

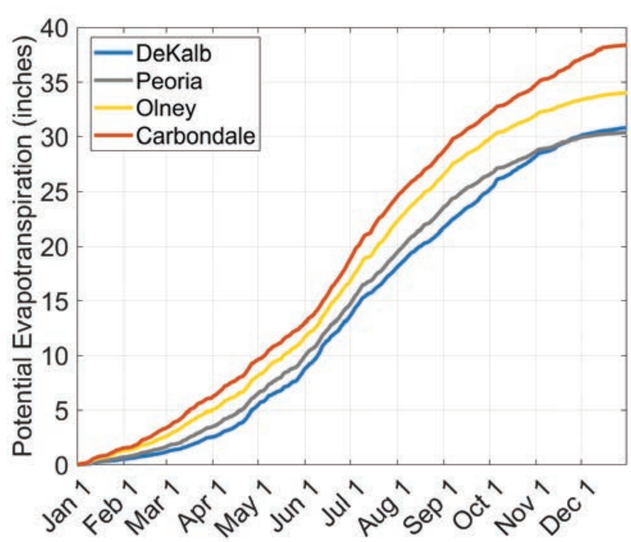

Figure 1.13. Average daily accumulation of potential evapotranspiration over the calendar year in DeKalb, Peoria, Olney, and Carbondale Illinois Climate Network stations. Averages are calculated over the period of 1991 to 2020

Table 1.1. Water content in the top 6-inch soil layer of a typical Illinois silt loam or silty clay loam during April, May, and June, and the minimum rain needed to bring soil moisture to field capacity.

Month	Dry		Average		Wet	
	Water content (in.)	Rain needed (in.)	Water content (in.)	Rain needed (in.)	Water content (in.)	Rain needed (in.)
April	1.5	0.7	1.9	0.3	2.4	0.0
May	1.2	1.1	1.6	0.7	2.2	0.1
June	0.9	1.4	1.5	0.8	2.0	0.3

of more daylight hours. Drought conditions occur when the potential evapotranspiration exceeds rainfall by more than the normal difference for several months in a row.

Soil Moisture

The amount of water held in the soil is determined by soil texture, soil drainage, precipitation, and evapotranspiration. During the summer months, evapotranspiration generally exceeds the rainwater absorbed by the soil, and the soil profile dries out. From October through April, evapotranspiration is usually less than precipitation, and the soil profile is recharged.

Wet soils in spring play an important role in determining how many days are suitable for field work. When soil moisture is normal or wetter than normal, even small rains will result in field work delays on all but the sandiest soils in Illinois. Rains greater than 0.10 inch often delay field work, especially in the spring and early summer, when soils are wettest. On average, there are 9 days each month with rainfall greater than 0.10 inch during May, 8 days each in April and June, 7 days each in July and August, and 6 days each in September and October.

During the spring planting season, the amount of water in the top 6 inches of soil controls field work activities. When the top 6 inches of soil is wet, planting is delayed, the nitrogen can be lost to either denitrification or leaching. Traffic on or tillage of fields when soil is near field capacity (80% of saturation) causes maximum compaction. During an average spring, soil moisture in April is great enough that rains of more than 0.3 inch will bring the soil water to field capacity. In the wettest years, rains greater than 0.3 inch result in significant periods of near-saturated soils in the upper 6 inches. The rainfall amounts shown in Table 1.1 are the minimum amounts of rain needed to trigger denitrification and provide optimum compaction conditions. When the subsurface soil levels are dry, more rain than the amounts shown is needed to have this effect. Only in the driest years will soils seldom reach field capacity.

Excessive soil moisture in late spring and early summer may result in loss of nitrogen through denitrification and leaching and may lead to the development of seed, root, and crown diseases. Conversely, dry soil during planting may result in poor stand establishment and may cause plant stress when dryness occurs during the periods of flowering and seed set.

The typical arable soil in Illinois is a silt loam or silty clay loam that will, on average, hold approximately 7.5 inches of plant-available water in the top 40 inches of soil. Plant-available water is defined as the amount of water in the soil between field capacity and wilting point. The wilting point is defined as the amount of water still in the soil when plants are unable to recover at night from wilting during the day. Illinois soils hold about 6.5 inches of water in the upper 40 inches of soil at the wilting point. Water in the top 40 inches of soil at saturation is approximately 14 inches. Individual soils vary significantly from the average. Coarse-textured soils, such as sands, hold less plant-available water and less water at the wilting point and field capacity than do fine-textured soils or soils with high clay content.

Whenever plant-available water in the top 40 inches of soil is less than 3.8 inches in June, July, or August, plants

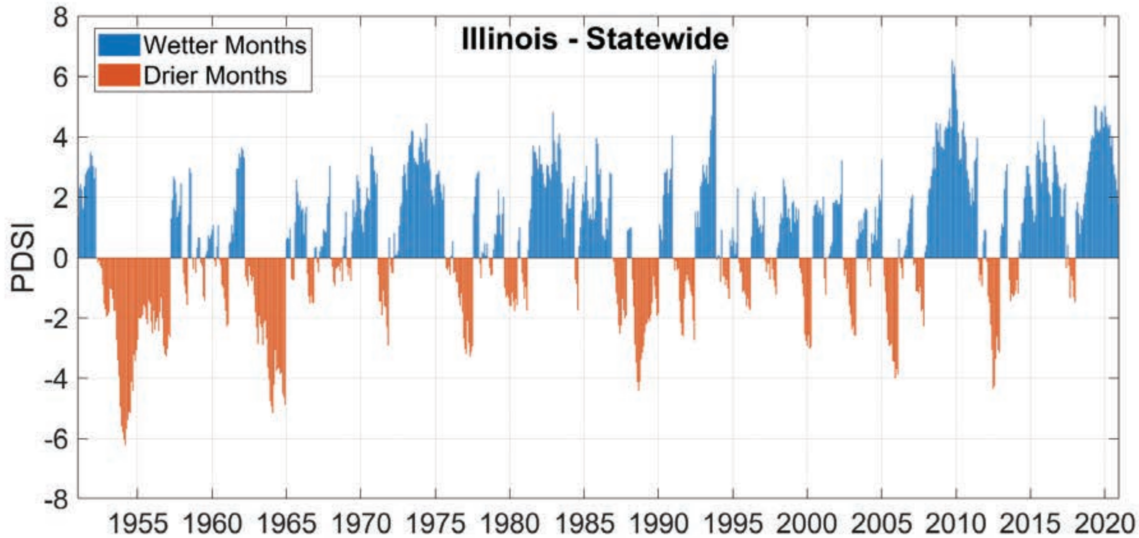

Figure 1.14. Statewide monthly Palmer Drought Severity Index (PDSI) from January 1951 to December 2020. Red bars indicate drier conditions, blue bars indicate wetter conditions.

will show significant moisture stress during the day. Soil moisture is generally below this limit only during the driest months of July and August. Even in these months, soil should experience soil periods above this stress threshold, especially following rains. In the wettest years, plant-available water exceeds plant needs, and periods of saturation may occur during the summer months.

Drought

Drought is a complex physical and social phenomenon of widespread significance, and despite all of the problems droughts have caused, they have been difficult to define. There is no universally accepted drought definition because drought, unlike flood or severe storms, is not a distinct event, and drought is often the result of many complex factors acting on and interacting with the environment. Complicating the problem of drought is the fact that drought often has neither a distinct start nor end. It is usually recognizable only after a period of time and, because a drought may be interrupted by short spells of one or more wet months, its termination is challenging to recognize.

Drought occurs in Illinois only when less than adequate precipitation exists for an extended period of time. Because of the complex nature of droughts, there are many definitions, often reflecting a specific area of concern of an individual, a city, or a region. The most commonly used drought definitions are: (1) Meteorological Drought – a period of well-below-average precipitation that spans from a month to a few years, (2) Agricultural Drought – a period when soil moisture is inadequate to meet the demands for crops to initiate and sustain plant growth, (3) Hydrological Drought – a period of below-average streamflow and/or depleted reservoir storage, (4) Socioeconomic Drought – a drought that affects the supply and demand of economic goods, and (5) Ecological Drought – a prolonged and widespread deficit in naturally available water supplies that creates multiple stresses across ecosystems.

One index that is frequently used to measure and monitor drought is the Palmer Drought Severity Index or PDSI. The PDSI estimates the anomaly of water balance (precipitation minus evapotranspiration) over a specified period, such as a month to a year. Negative values of PDSI indicate moisture deficit and values less than -2 during the growing season are typically associated with crop stress. Figure 1.14 shows the time series of statewide-average monthly PDSI between 1951 and 2020. Illinois experienced more frequent and persistent droughts earlier in this time period, particularly in the 1950s and 1960s. Although there have been significant droughts since 1990 such as those in 2005 and 2012, they

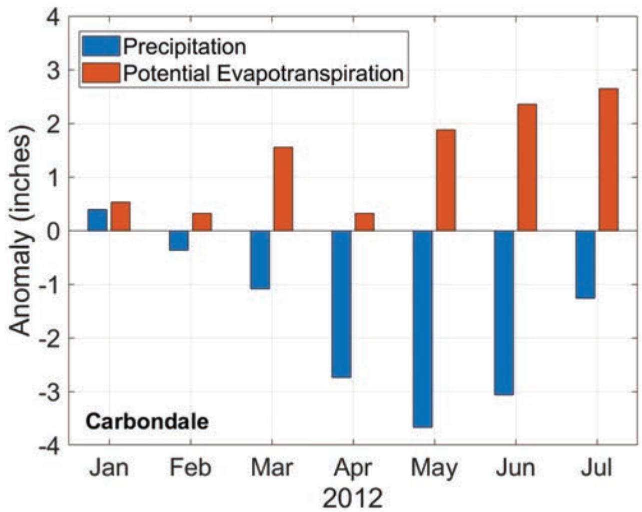

Figure 1.15. Monthly precipitation and potential evapotranspiration anomolies from January to July 2012 in Carbondale.

are less frequent and less persistent. This is partly due to concurrent increases in precipitation across the state.

Flash Drought: Drought is typically considered a slowly evolving hazard that takes months, if not years, to develop and intensify. However, recent drought events such as the 2012 drought in the Midwest developed and intensified much more quickly than past droughts. Consequently, the term "flash drought" has been popularized to refer to droughts that onset or intensify more quickly than normal in a region. Much like slower evolving drought, below-normal precipitation is necessary for a region to experience flash drought; however, the drought rapid onset or intensification is caused by dry conditions that are exacerbated by very high potential evapotranspiration, driven by unusually high temperatures, low humidity, and abundant sunshine.

Figure 1.15 shows monthly precipitation and potential evapotranspiration anomalies from January to July 2012 in Carbondale. Precipitation in April, May, and June each was 2.5 to 3.5 inches below average while potential evapotranspiration was 1 to 3 inches above average. The combination of below average precipitation and above average evaporative demand quickly depleted soil moisture in late spring and early summer across the state. This resulted in significant crop moisture stress and statewide yields that were well below the long-term trend.

Solar Radiation

Plants use the solar energy from the sun to fix carbon dioxide from the atmosphere, in combination with water from the soil, into carbohydrates that cause plants to grow, reproduce, and provide the grain and vegetation used as food by humans and animals. The solar energy available to plants is a function of sunshine intensity and duration. In southern Illinois the intensity of sunshine is greater than in the northern regions. The greater intensity of sunshine in the south does not translate to significantly more total solar energy available in a single day compared to the north because the longer days during the summer in the north offset the lower intensity sunshine with more hours of sunshine.

Total daily solar energy received at the Earth's surface has units of megajoules per square meter per day ($MJ/m^2/day$). The average solar energy received by a crop around the summer solstice is approximately 25 $MJ/m^2/day$ (Figure 1.16). At the spring equinox, average total solar energy is approximately 15 $MJ/m^2/day$, and at the autumn equinox approximately 16 $MJ/m^2/day$.

A question often asked is how cloudiness and low solar radiation affect yields. New technology allows continuous measurement of the exchange of CO2 between the atmosphere and the earth's surface. When plants are fixing CO2 through the process of photosynthesis, the flux of CO2 is toward the surface.

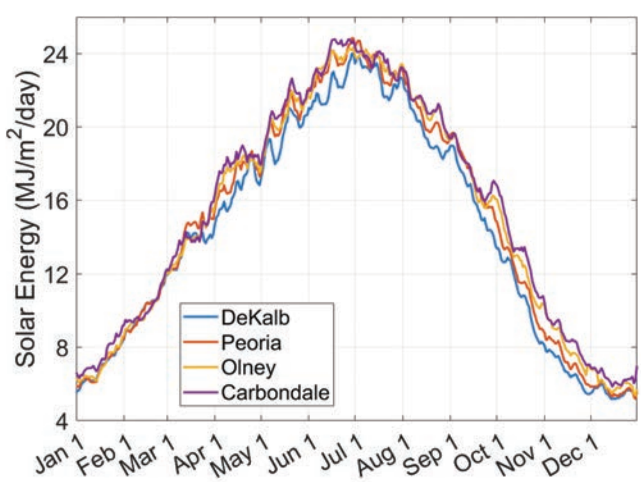

Figure 1.16. Average daily solar energy over the calendar year in DeKalb, Peoria, Olney, and Carbondale Illinois Climate Network stations. Averages are calculated over the period of 1991 to 2020

By summing the quantity of CO_2 that is being fixed by the plant over the daylight hours and simultaneously measuring the solar energy available to the crop, the efficiency of solar energy use by the crop can be estimated. The carbon fixation rates given below were obtained from data gathered over 4 years of corn and 4 years of soybean CO_2 flux monitoring in central Illinois.

A heavily overcast day in this discussion means no shadows would be seen at any time. An average day is one when light shadows would be seen, such as on a very hazy day when the sky has a blue-gray appearance or when the skies are partly cloudy and there are periods of both full sun and full shade (when no shadows are visible). A clear sunny day is characterized by deep blue skies with no clouds visible.

When the crop has a full canopy (i.e., a leaf area index greater than 2.7), the rate of carbon fixation by corn results in an accumulation of approximately 0.14 bushels of grain per acre per megajoule—bu/A/MJ. An average heavily overcast day between May and August receives about 8.2 MJ of solar energy. Thus, if all the carbon fixed by photosynthesis were to go into the grain, the yield gain on a heavily overcast day would be 1.2 bu/A/day. The average daily solar energy received during the same period is about 21.7 MJ, which translates into about 3.1 bu/A. On an average clear sunny day, the daily solar energy available to the crop is approximately 29.7 MJ, producing about 4.3 bu/A of grain during the day. Therefore, on a heavily overcast day, approximately 1 bu/A would be lost compared to an average day, and an additional 1.2 bu/A would be gained on a clear day compared to an average day.

The average rate of carbon fixation by soybean results in an accumulation of about 0.07 bu/A/MJ. Thus, on a heavily overcast day, about 0.6 bu/A would accumulate, while on an average day, 1.5 bu/A would accumulate, and on a clear sunny day, 2.0 bu/A would accumulate. Compared to an average summer day, the yield loss on a heavily overcast day would be approximately 0.9 bu/A, and the yield gain on a clear day would be 0.5 bu/A. These estimates are just rules of thumb and cannot precisely specify yield loss due to cloudiness. Further, the rate of carbon fixation depends on the supply of water and minerals and the presence or absence of disease and insects. If there is an adequate supply of water and minerals without the presence of disease or insects, the rate of carbon fixation may be greater than the rates given here. Conversely, if the supply of water or minerals is not adequate, or there is disease or insect pressure on the crop, the rate of carbon fixation will be lower than the rate given here, and yields will be lower. With higher carbon fixation rates under optimum growing conditions, the effect of cloudiness will be greater. Under suboptimal growing conditions, the effect of cloudiness will be less.

Climate-related Decision Support Tools

Useful to Usable (U2U) was a multi-year, multi-university integrated research and extension project, funded by the USDA's National Institute of Food and Agriculture. Its mission was to improve farm resilience and profitability in the North Central U.S. by transforming existing climate data into usable products for the agricultural community. A suite of decision-support tools was a product of this effort to help producers make better long-term decisions on what, when, and where to plant, and how to manage crops for maximum yields and minimum environmental damage. These tools are hosted by Midwestern Regional Climate center (MRCC) at https://mrcc.purdue.edu/U2U/.

The AgClimate Viewer is a convenient way to access customized historical climate and crop yield data for the U.S. Corn Belt. One can view graphs of monthly temperature and precipitation, plot corn and soybean yield trends, and compare climate and yields over the past 30 years for the selected county. The Corn GDD Tool (Figure 1.17) tracks both real-time and historical GDD accumulations, assesses spring and fall frost risk, and guides decisions related to planting, harvest, and seed selection. This innovative tool integrates corn development stages with weather and climate data for location-specific decision support tailored specifically to agricultural production. The Climate Patterns Viewer links global climate patterns like the El Niño

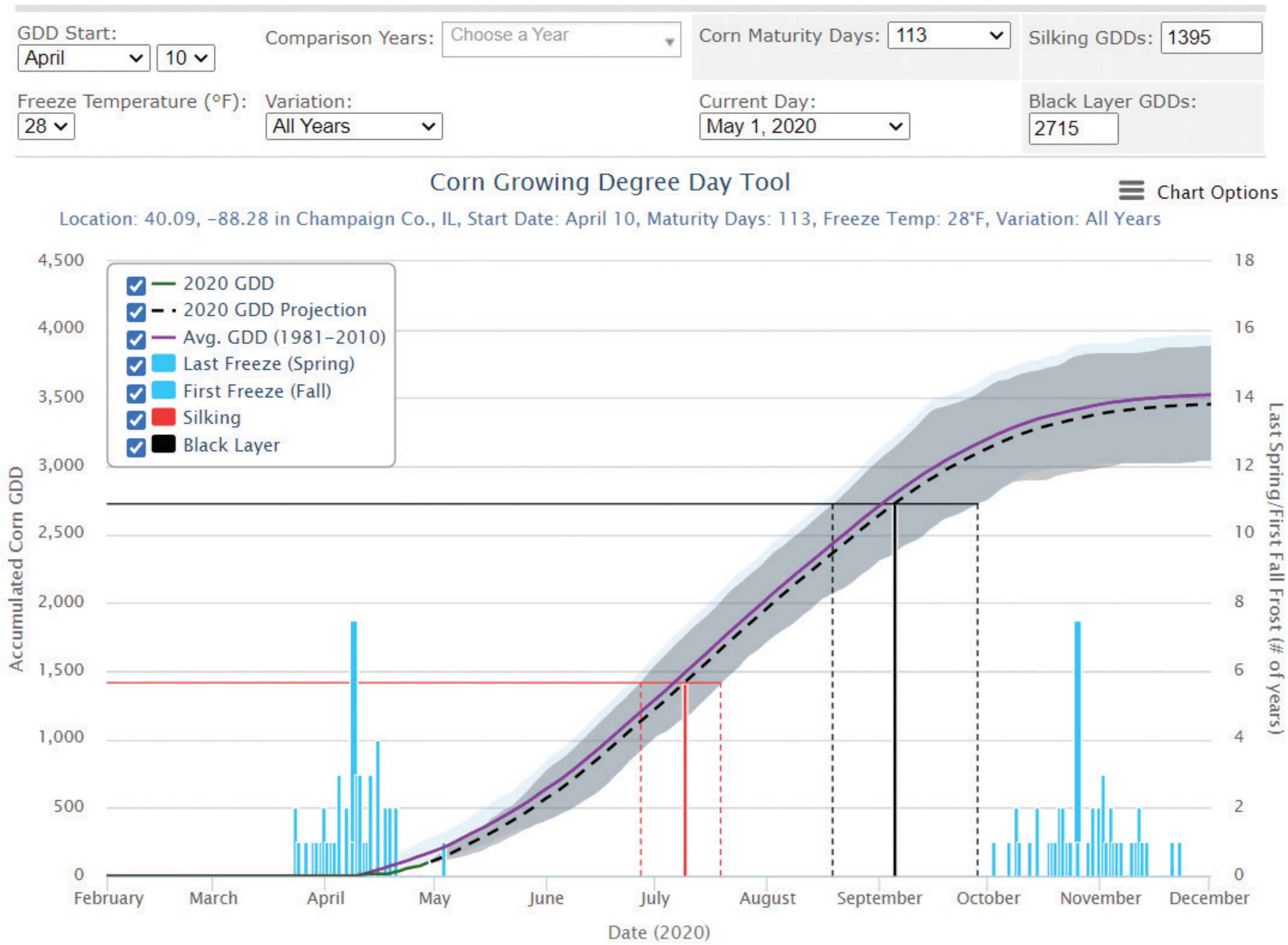

Figure 1.17 A screenshot of the Corn GDD tool based on conditions on May 1, 2020. For the chosen county, the tool shows the risk of the last spring and first fall frost, projections of GDD accumulations for the rest of the season based on historical and forecasted temperatures, and the estimated time of the silking and black layer formation in corn. Factors such as planting date, corn maturity, freeze dates and comparison years can be chosen by the user.

Southern Oscillation (ENSO) and Arctic Oscillation (AO) to historical local climate conditions and crop yields across the U.S. Corn Belt.

The Corn Split N Tool determines the feasibility and profitability of using post-planting nitrogen application for corn production. This product combines historical data on crop growth and fieldwork conditions with economic considerations to determine best/worst/average scenarios of successfully completing nitrogen applications within a user-specified time period. Now available for 12 states in the north central U.S. The Irrigation Investment Tool lets you explore the potential profitability of installing irrigation equipment at user-selected locations across the Corn Belt. Discover how many years from 1980-2005 irrigation would have been profitable, calculate the net present value of investment, and compare dryland and irrigated corn and soybean yields under different rainfall conditions. Finally, the Probable Fieldwork Days Tool uses USDA data on Days Suitable for Fieldwork to determine the probability of completing in-field activities during a user-specified time period. Hosted by the University of Missouri, this product is currently available for Illinois, Iowa, Kansas, and Missouri.