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Agricultural Meteorology and Crop Production on the Canadian Prairie: Solar Radiation, Temperature and Water

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Summary
Agricultural meteorology is the study of how climate and weather impact agricultural systems. Solar energy, in the form of radiation, is the driver behind the regional distribution of climate and weather across the surface of the earth. After long time periods climate and weather become somewhat unique to a given region. Regional differences in, for example, solar radiation, temperature, precipitation, wind and humidity are identifiable and contribute to determining the agricultural practices that are practical and profitable in a given region. Although the energy budget and water balance vary across regions, there are basic principles for solar energy, temperature and water availability that can be applied independent of regions.

Introduction
Agricultural systems including living organisms (such as crops, livestock, and microbes) and other components (such as soil) are all affected by meteorological factors, most notably solar radiation, temperature, and water availability (including precipitation and evaporation). Although solar radiation is the driver behind climate and weather, the most noticeable and easily measureable weather parameters that have, arguably, the greatest impact on agriculture are temperature and water availability. Generally, water availability is the major limitation to agricultural production on the Canadian prairies. However, there are regions for example where low spring soil temperatures provide major limitations to seed germination and ultimately yields. Within a given region, producers tend to 'push the boundaries' to maximize profits and yet remain economically viable. The boundaries are different for each region. Fundamental to the development of crop production practices is knowledge of crop response to solar radiation, temperature and water availability and their interactions.

Solar radiation (solar energy)
Solar radiation is the energy the earth receives from the sun. The intensity of the energy emitted by an object is proportional to the objects surface temperature. The sun's surface temperature averages about 5800 °C. The radiant energy emitted by the sun is often referred to as short-wave radiation. The average temperature of the earth's surface is about 15 °C. The radiant energy emitted by the earth is often referred to as long-wave radiation. The lower the surface temperature and the longer the wavelength, the lower the intensity of the energy emitted. The energy emitted by the sun far exceeds that emitted by the earth or any object on or near the earth's surface.

Net Radiation
Solar radiation is the primary, if not the ultimate energy source for all physical and biological processes occurring on the earth[1]. Agriculture has been defined as an exploitation of solar energy, made possible by an adequate supply of water and nutrients to maintain growth[2]. Solar radiation provides the energy that fuels weather fluctuations[3]. Temperature change can occur with uneven absorption of solar radiation by bodies of different densities and heat storage capacities such as air, soil and water. Wind occurs when latent and sensible heat move though the atmosphere causing the air molecules to move at different rates. Local thunderstorms and convective showers can develop under high humidity conditions with the capture of latent heat at the earth's surface (evaporation) and release of latent heat in the atmosphere (condensation).

Net radiation (Rn) absorbed by a vegetative surface is the balance between incoming and outgoing radiation. Incoming radiation includes incident solar radiation emitted by the sun plus long-wave radiation from the atmosphere and surroundings that are absorbed by the vegetative surface. Outgoing radiation includes reflected and transmitted solar radiation plus long-wave radiation emitted from the vegetative surface[4]. Of the solar radiation entering the earth's atmosphere, roughly 50% of incoming radiation is absorbed by the land and oceans (earth's surface), 30% is reflected back to space and 20% is absorbed by the atmosphere and clouds[3]. Incoming radiation acts to warm the object whereas outgoing radiation acts to cool the object. Outgoing long-wave radiation emitted by the surface of an object is dependent on the temperature of that object. Outgoing long-wave radiation from an object is greater than the incoming long-wave radiation from the atmosphere[5]. Generally, on a yearly basis, daily total Rn on the Canadian prairie is positive except for the winter months when Rn is negative, especially with snow cover. On a daily basis, for clear days during the summer months Rn is negative during the night and is generally positive from shortly after dawn until shortly before dusk.

An equation to represent the inputs, losses and storage of energy when solar radiation is absorbed by a vegetative surface is:

$$Rn=M+G+H+\lambda E$$

where Rn is the net radiation absorbed by the surface; M refers to the energy used in net plant photosynthesis; G refers to heat storage in the vegetation, soil and air; H refers to sensible heat loss (heat flow or heat loss from the surface by conduction and/or convection due to a temperature difference across the surface); and λE refers to latent heat loss from the surface (E is the rate of evaporation of water from the surface and λ is the heat absorbed when a gram of water evaporates)[6]. Sensible heat is the energy required to change the temperature of a substance without a phase change. Latent heat is the energy absorbed by or released from a substance during a phase change. A substance absorbs energy from its surroundings to change from its higher density liquid phase to its lower density gas phase; energy is released to its surroundings when the reverse occurs. For example, evaporation of water requires energy from the surroundings to change from the liquid phase to the gas phase (water vapour); condensation releases energy to the surroundings when water changes from the gas (water vapour) phase to the liquid (water) phase. Conduction is the transfer of heat to a substance of lower temperature which comes in direct contact with a substance of higher temperature, for example, air coming in contact with pavement warmed by the sun[6]. Convection is the transport of heat in a moving fluid such as air, i.e., wind. Wind decreases the thickness of the boundary layer (discussed later) between the surface and the air in motion accelerating the transfer of heat from the surface to the air. For example, heat is transferred by conduction to air in contact with hot pavement, and wind (air in motion) carries the heat transferred to the air away from the site of conduction. If the air is warmer than the surface, sensible heat flows across the surface into the plant and thus warming the plant. Evaporation of water from the surface is a very effective way of cooling the plant. However, in very hot conditions the plant may shut down (plant closes the stomata) and loose the cooling effect of water evaporation. The temperature of the plant will increase (in some cases very quickly) in response to the absorption of sensible heat that is not counter balanced by water evaporation. These principles apply to the human body as well. Under very hot conditions, the body stops sweating and loses the cooling effect of evaporation. Sensible heat penetrates the skin heating the body. These conditions can result in heat stroke, a very dangerous situation that can led to death.

Photosynthesis

Essentially, life as we know it exists because of photosynthesis, which is the only significant mechanism for incorporating energy into life on earth. Photosynthesis is a complex process of physical and chemical reactions, most often occurring within plant leaves, whereby sunlight provides the energy needed to convert carbon dioxide and water into carbohydrates and oxygen[7], i.e., carbon dioxide + water + light energy → glucose (sugar) + oxygen. Because of the requirement for solar energy, the light reactions of photosynthesis occur during daylight hours. Carbohydrates are precursors to the compounds ('building blocks') that are eventually used to increase overall plant (crop) biomass. These 'building blocks' are partitioned between leaves, stems, roots, seeds, etc[8].

Respiration is the process whereby sugar compounds (photosynthates) are broken down to release the energy stored in the sugars. Respiration is the opposite of photosynthesis, i.e., glucose (sugar) + oxygen → energy + carbon dioxide + water. Respiration does not require energy from the sun and therefore occurs day and night. A large portion of the energy released during respiration is heat, whereas a small portion of the energy is trapped in compounds that are later transported and used when energy is needed to complete various growth processes.

Photosynthesis and respiration occur simultaneously. Net photosynthesis is the difference between carbon dioxide incorporated into the plant by photosynthesis and that lost from the plant by respiration. Net photosynthesis is positive or plant biomass would not increase.

Attenuation of solar energy by the atmosphere

Solar radiation at the earth's surface is a fraction of the solar radiation at the top of the atmosphere. Nature and human activities release atmospheric emissions that change the composition of the atmosphere and disrupt the balance between incoming and outgoing radiant energy[9]. Natural disruptions to the energy balance include volcanic emissions into the atmosphere resulting in global cooling[10]. Industrial and agricultural emissions of greenhouse gases (such as CO_2-carbon dioxide, N_2O nitrous oxide, CH_4-methane) contribute to global warming by preventing long-wave radiation from escaping the earth's atmosphere into outer space. Other gas emissions (such as SO_2-sulpher dioxide) and aerosols (such as soot) contribute to global cooling by blocking or reflecting incoming solar radiation back into outer space[9]. A warming atmosphere holds more water[11]. Solar radiation reaching the earth's surface is very dependent upon the water vapour content of the atmosphere. Clouds are very strong modifiers of surface solar radiation[9]. Clouds reflect incoming solar radiation back to outer space; a smaller portion is absorbed by the water molecules, while the remaining portion passes through the cloud. As well, clouds reduce the amount of long-wave radiation escaping the atmosphere to outer space. Overall, increased cloudiness acts to reduce global warming. Increase in greenhouse gas concentrations leads to a reduction of cloudiness promoting global warming whereas increasing aerosol concentrations often increase cloudiness[12].

Temperature

Within a given body, whether soil, plant or human, atoms and molecules are always in motion, and because they are in motion they have kinetic energy. Temperature measures the average kinetic energy of the body. Temperature does not measure the heat content of a body (soil has a much greater heat storage capacity than air) but measures the intensity of that heat[13]. Add heat to a system, particles move faster (increase in kinetic energy), and temperature increases.

Cardinal temperatures

For a majority of growth processes (such as rates of photosynthesis, respiration, root growth and water uptake, dry matter increase, grain yield, phenological development) plants have a minimum temperature below which the process stops (cold stress such as frost), an optimum temperature or range of temperatures at which the process proceeds at a maximum rate, and a maximum temperature above which the process stops (heat stress). These temperatures are referred to as cardinal temperatures and are dependent upon variety, and the growth process occurring within that variety[14]. For example, the cardinal temperatures for the development rate from emergence to terminal spikelet initiation for Barrie spring wheat are: minimum temperature, 0°C; optimum temperature, about 23°C; maximum temperature, 36°C. For winter cereals, the optimum temperature was about 12°C (Fig. 1).

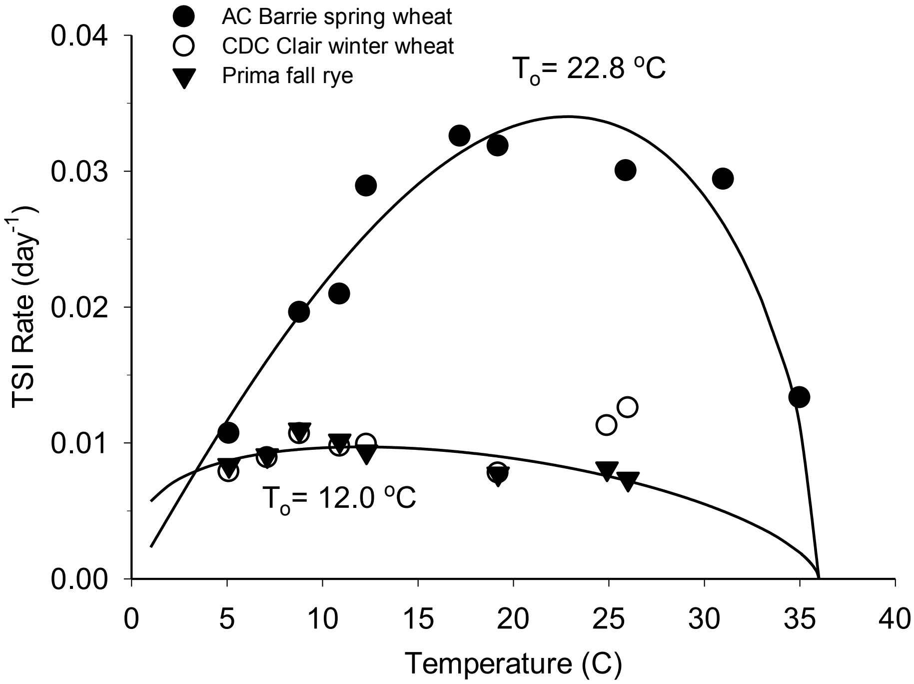

Fig. 1. Temperature response functions for terminal spikelet initiation (TSI) rate (reciprocal of days between the germination to terminal spikelet initiation stages) versus temperature for AC Barrie spring wheat and the winter cereals, CDC Clair winter wheat and Prima fall rye.

Heat stress

Heat stress is often confounded by water stress, because both usually accompany each other[15]. In water stressed plants, the cooling effect of transpiration decreases, and as a result plant temperature increases[15]. The upper temperature for high temperature stress varies for example with species, organ, and phenological development. The optimum temperature range for photosynthesis in wheat is between 15 and 30°C, above 40°C the photosynthetic machinery breaks down often resulting in permanent damage. Analysis of 50 years of field-grown test plots across the Canadian prairie indicated that temperatures >24°C in early June and temperatures >20°C during the first 3 weeks of July may reduce yields of durum wheat[16]. The maximum temperature for spikelet initiation in wheat is >25°C[17]. On average, early June is about the time when the apical meristem is transitioning from the vegetative stage to the reproductive stage at which time the spikelet primordia are differentiating. From this stage to shortly before terminal spikelet initiation, high temperature stress will reduce the number of spikelets per head thereby reducing yield[18]. Further, on average, heading and anthesis occur during the first 3 weeks of July. Yield of wheat is very sensitive to high temperatures 5 to 10 days before anthesis because at this time pollen viability is established[19].

Cold stress: Frost

Plants that have experienced several cycles of mild low temperatures tend to be able to tolerate lower temperatures better than they would have initially tolerated without a "hardening process"[15]. Plants, such as canola, wheat, chickpea, especially at the seedling stage, that have been hardened to low temperatures can survive temperatures ≤ -8°C[20,21]. Further, after several cycles of high temperature and/or water stress, there are plant species that will harden and be able to withstand higher stress levels than normal. Because of the hardening process, the killing frost-free duration (KFFD) provides an estimate of the growing season for a region. KFFD is the duration (days) between the last spring killing frost (LSKF) date at -8°C and first fall killing frost (FFKF) date at -2°C[22]. The grain filling process for several crops can function at ≤ -2°C[23].

Water availability

Evapotranspiration of water

Evapotranspiration is the total water lost from a crop and is equivalent to plant transpiration plus evaporation from plant surfaces, residue and soil[24]. Transpiration is the evaporation of water from stomata located mostly on the underside of leaves, with a few located on stems. Stomata are structures on leaves consisting of a large pore sunk into the leaf with two guard cells at the mouth of the pore. In response to one or several environmental factors, guard cells regulate transpirational water losses by opening or closing the entrance to stomata. When the stomata are fully open, transpiration is proportional to the available energy. For a given environment, when the stomata partially close, the transpiration rate is reduced and is proportional to solar radiant energy[25].

Transpiration rate is dependent on temperature, humidity and wind. Generally, for every 10°C rise in temperature, the transpiration rate doubles[26]. However, transpiration and evaporation from the pore surface cools the leaf so that leaf temperature does not increase as quickly as air temperature. Humidity is a measure of how much water vapor is in the air. For a given environment, the transpiration rate is lower in air with high humidity compared to air with low humidity.

The boundary layer is a layer of still air adjacent to a leaf surface or a crop canopy. The boundary layer provides some resistance to water movement (and temperature exchange) from the leaf to the moving air above the boundary layer; the thicker the boundary layer the greater resistance to water movement (temperature exchange) across the layer. The thicker the boundary layer the lower the water loss from the plant via transpiration through the stomata or evaporation from plant surfaces such as leaves and stems. The thickness of the boundary layer is affected by wind speed; the greater the wind speed, the thinner the boundary layer, and the less resistance the boundary layer has to water vapour movement from the leaf to the moving air above the boundary layer.

Potential evapotranspiration

Actual evapotranspiration reaches potential evapotranspiration (PE) when water is abundant, i.e. water is not a limiting factor to evaporation. Potential evapotranspiration has been defined as 'the amount of water transpired in unit time by a short, green crop, completely shading the ground, of uniform height and never short of water.'[27] The conditions under which Penman developed the concept of potential evaporation made no provision for advected energy, which provides significant amounts of energy to the evaporation process in arid climates such as the Brown and Dark Brown soil zones on the Canadian prairie. Evaporation of water from a Class 'A' evaporation pan is a good estimator of potential evaporation, especially under arid to semiarid conditions. The potential evaporation rate of air, i.e., evaporative demand, is a function of solar radiation, temperature, wind and humidity in the ratio 80:14:6, where temperature and radiation have been combined[28].

The agricultural region of the Canadian Prairies can be separated into dryer to wetter soil zones (Table 1). Compared to the wetter soil zones, the dryer soil zones tend to have higher average annual wind speeds and temperatures contributing to higher potential evaporation (ET_p).

Water deficit

Water deficit is the potential evaporation (atmospheric demand or atmospheric affinity for water) minus available water (ability to meet or satisfy that demand), i.e., water deficit = potential evaporation (PE) - available water. Generally, the higher the deficit, the lower the crop yields. This linear relationship is independent of scale, i.e., applies across the agricultural region of the prairies as well as for individual fields. Comparing across soil zones (Fig. 2), there is a linear relationship between wheat yield and water deficit (Fig. 3). (For this case available water was the yearly total precipitation). Further, based on a long-term crop rotation study (1967-2007, 41 years) at Swift Current, there is a linear relationship between wheat yields and water deficits (Fig. 4). (For the purpose of this study, the available water was calculated as the growing season rainfall plus the available soil water between seeding and harvest.)

Table 1. Climate measurements at several Agricultural and Food Canada research centers on the Prairies including mean annual windspeed, temperature and precipitation, total May through September potential evaporation (Class 'A' pan) (ET_p), and deficit (Deficit = ET_p - Precip).

Location	Wind ($km\ h^{-1}$)	Temp. (^oC)	Precip. (mm)	ET_p (mm)	Deficit (mm)	Yield ($kg\ h^{-1}$)
Brown soil zone						
Swift Current	22.9	3.3	334	822	488	1233
Dark Brown soil zone						
Lethbridge	20.4	5.0	413	759	346	1585
Scott	14.5	1.0	355	716	361	1633
Black soil zone						
Lacombe	10.9	2.1	443	457	14	--
Melfort	15.4	0.3	411	620	209	1770
Indian Head	15.8	2.0	427	598	171	1640
Brandon	16.3	1.9	485	630	145	--
Dark Gray soil zone						
Beaverlodge	12.2	1.6	467	604	137	2050

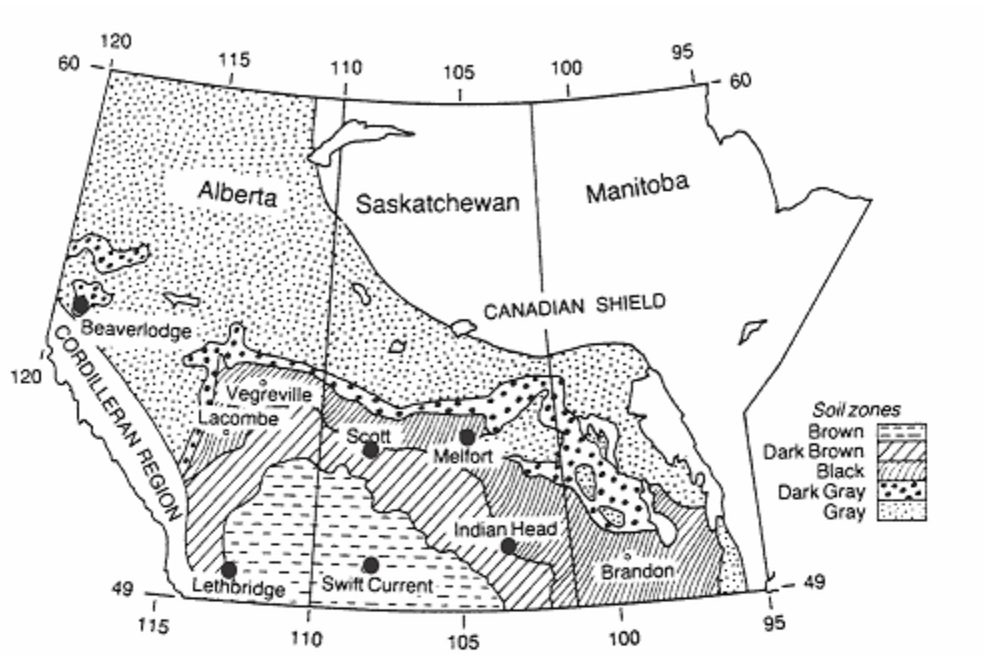

Fig. 2. Location of AAFC research stations and major soil zones of the Canadian prairie.

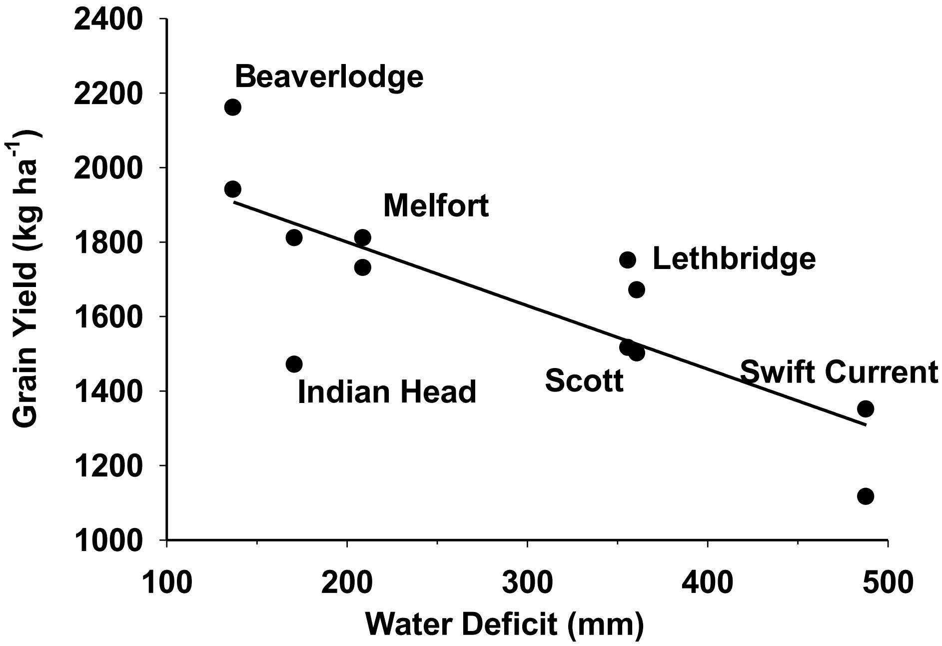

Fig. 3. Comparing across the major soil zones in the Canadian prairie, relationship between yield and water deficit for spring wheat grown on fallow and stubble at each of the AAFC research stations highlighted in Fig. 2.

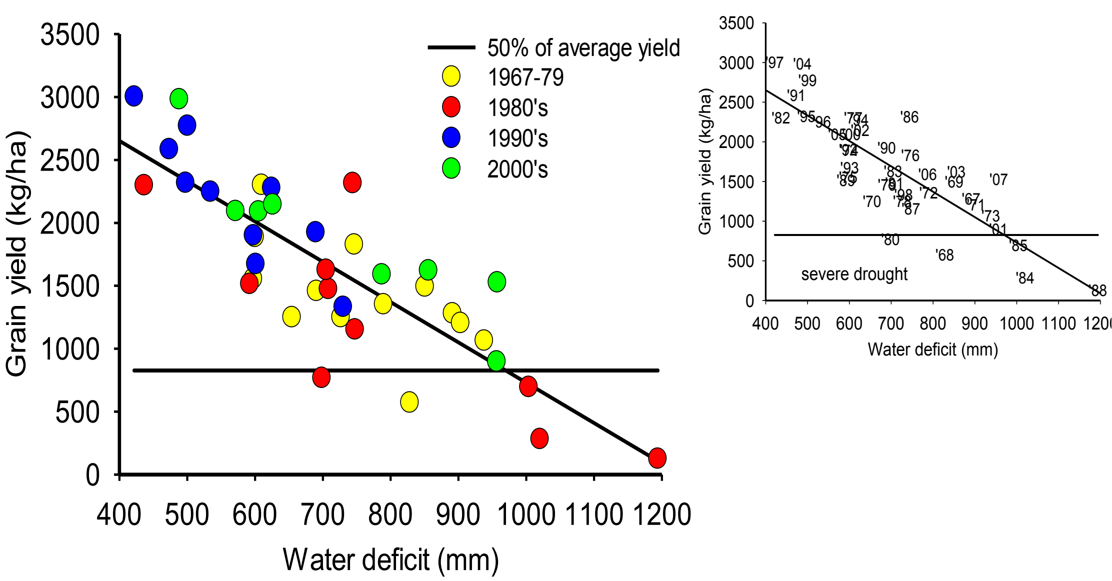

Fig. 4. For the same field at the AAFC research station near Swift Current, the linear relationship between the yield of spring wheat and water deficit from 1967 to 2007. The relationship is identified by decade, and by years. Severe drought occurred when the yield fell below 50% of the average yield. Average yield=1652 kg ha^{-1}, 50% of average=826 kg ha^{-1}.

Drought

Drought on the Canadian prairies severely limits crop production, especially for the Brown and Dark Brown soil zones. To agricultural producers in both the wetter and drier regions of the Canadian prairies, drought means the same thing - a severe lack of water and often a drastic reduction in crop yield. While its impact is clearly visible, it is often difficult to define. One definition of drought is 'a period, generally in the order of months or years, when the water supply of a region is consistently below long-term averages.'

For the Swift Current area, we assumed that a drought occurs when yields are drastically reduced below the long-term average yield of 1652 kg ha^{-1}. Severe droughts that reduced yields by at least 50% below the average (826 kg ha^{-1}) have occurred in 5 of the 41 years between 1967 and 2007 (Fig. 4). The water deficit at the occurrence of the long-term average yield is 712 mm and 970 mm when 50% of the long-term average yield occurs. Droughts usually result from a combination of high rates of evaporation (from the soil and plants) and low amounts of precipitation, as occurred in 1968, 1984 and 1985. Occasionally, there are years when precipitation is near normal but the evaporative demand of the atmosphere far exceeds the water available to meet the demand, as occurred in 1988 with record rates of evaporation in each of May, June, and July.

Agricultural meteorology provides understanding of crop-climate relationships. Working in conjunction with other disciplines such as agronomy and soil fertility, production practices are developed that enable producers to be sustainable and economically viable. Further, identifying production practices that mitigate climate and weather extremes enhance sustainability by enabling production over a wider range of temperatures and water availabilities. For example, developing production practices that minimize the effects of drought on crop growth and yield by enabling a crop to avoid drought and/or tolerate short periods of drought. These practices enable producers to be better prepared and proactive rather than reactive towards stresses on crop production.

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