Weather extremes that impact various agricultural commodities

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ABSTRACT

Broad scale weather extremes that impact yield are tabulated for several agricultural commodities organized into 13 groupings. How these weather metrics cause harm is also discussed briefly in the context of each commodity. Cultivars have differing properties, so most thresholds are somewhat imprecise, though threshold temperatures near freezing and near 35-40C are common. Timing is critical to the impact of an extreme and the most critical time for crops extends from just before flowering until the next 1-2 months. Sometimes the extreme does not cause the impact but sets in motion physiological changes making the plant vulnerable to near normal weather later. Beyond mortality and morbidity thresholds, combinations of atmospheric variables are important, such as high humidity with high temperatures.

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1. INTRODUCTION

What weather extremes impact various agricultural commodities? Temperatures that sunscald apples and halt flowering tomatoes are just what ripening pistachios need. Yields suffer when dormant walnuts have too little chill just as flowering rice does with too much heat. When do winds matter? Can humidity be too ‘extreme’? This chapter examines critical meteorological factors in 13 agricultural commodity groupings. The diversity of agricultural products is vast, so many commodities are not covered. Some commodities are skipped because the environment is highly managed (e.g. poultry).

This chapter is motivated to help climate modelers interpret the impacts in their output. A statistical quantity like TX95, the 95th percentile value of daily maximum temperature, often has little bearing on what impacts an agricultural product. The climate literature has considered more relevant but still basic quantities (e.g. Terando et al., 2012). Crop models are now being driven by detailed climate model output to estimate impacts of possible future climates. This chapter collects a more nuanced set of basic extreme metrics, though less complex than crop models need.

There are mortality thresholds and dormancy thresholds. But when an extreme happens is often more important than the value of the weather parameter. Frost dates are one of the few agriculture-useful quantities in the general climate science literature; but timing is critical. The critical timing is not much keyed to a calendar, but instead to the *physiological time* of the crop. Plants are integrators of conditions over time, but swings in temperature have different consequences than a constant average of those swings. Plants have limits that change over time. Hence, collecting those thresholds and limits in one place provides a useful 'lookup table' for climate scientists when paired with an explanation for why that weather is a critical factor.

December 1983 had temperatures in Florida’s citrus growing region that were just above average. The monthly mean temperature was 0.8C *above* normal in Winter Haven, Florida. That is the good news. The bad news is >80% of the juicing oranges were spoiled and more than half of the citrus *trees* were killed that month. Two days that month had extremely cold minimum temperatures (Tmin) for the region: 15C below average. The point of this anecdote is that extremes happen on short and long time scales. Sometimes an important ‘flash’ extreme belies the longer term average.

Crops go through development stages called a *phenology*. There are developmental temperature thresholds, such as a temperature below which development stops. For example, banana plants go dormant below ~18C; as do citrus flowers below ~9C. Growth rates decrease or stop above certain thresholds. Time spent in each stage is termed *physiological time* and is estimated using accumulating metrics, like chilling hours (CH) or growing degree hours (GDH). Chilling hours are cumulative hours below a threshold (e.g. 7C) and often above a lower value (e.g. 1C) during winter months. CH measures the time needed for sufficient dormancy so the plant is ready break dormancy; while the plant breaks dormancy for fewer CH, blooming may be irregular and sub-optimal resulting in (much) lower yields. GDH is a bit more complex.

Many factors affect yield and the impact of a specific weather event varies. Timing in growth cycle is mentioned above. Often, plants are most sensitive to extreme temperatures during flowering (‘anthesis’) when pollination and nascent fruit set occur. When flowering occurs and how long the nascent fruit are vulnerable depend on the physiological time (e.g. when a GDH threshold is reached). Fruit drop early in the season for many tree crops diminishes yield irreversibly for the year. Other crops (e.g. soybean) can re-bloom and recover some yield. Also, while thresholds will be given below, they are not necessarily hard limits. For example, duration matters for a plant sensitive to freezing (e.g. lime) as cold slowly penetrates plant tissues (such as a limb), alternatively, soft tissues (e.g. tomato leaves) exposed to clear night skies can be harmed during above freezing temperatures. So, duration below a threshold matters: two degrees below a threshold for two hours might have similar consequences as one degree below for four hours. A high threshold may mark a point where production of fruit is not halted but becomes increasingly impaired as temperature rises further (e.g. maize).

The diurnal cycle of temperature over a day affects duration. In some tables below, the diurnal range may be assumed and the extreme temperature cited may be the *daily average*, implying maximum temperatures (Tmax) being higher (by 5C, say). This distinction is too often not clear in the literature. Since daily average temperature can be relevant, one needs to consider daily minimum temperatures (Tmin) too. Tmin may be rising faster than daily maxima (Vose et al., 2005) causing the diurnal temperature range to decrease. The trends are larger in winter than summer in the Northern Hemisphere, though summer has the same sign as winter in all the trends (Davy et al., 2017).

Accordingly, crops are sometimes described using the ‘cardinal temperatures’ which consist of a minimum or ‘base’ temperature (Tb) threshold, an optimal temperature or range, and a maximum or ‘damaging’ temperature threshold (e.g. Prasad and Djanaguiraman, 2014).

Often an extreme of temperature may be amplified by the moisture present, either too much humidity (so the plant is inefficient at cooling by transpiration) or too little humidity (so pollen is viable for a shorter time). Similarly, water use and precipitation requirements mentioned are rough guidelines since plant water use strongly varies with current and past atmospheric and soil conditions.

This analysis is limited by factors other than climate being important. Varieties differ. Water quality, water availability, soil quality, and pest pressure vary. Plants adapted for local conditions may be harmed by a relative change that might not exceed an absolute threshold (e.g. 5C above average; De Boeck et al., 2010). For example, desert varieties of peaches have 1/5 the CH requirement of cold-adapted varieties. For stone and pome fruits as well as the tree nuts discussed here, what happened the prior year (when buds were forming) impacts yield the following year. Other factors alter the hard numbers: Hatfield et al. (2011) emphasize that plant temperature can be higher (lower) than air temperature, by up to 10C, if the plant is stressed (or not) (e.g. Campbell et al., 1990).

Despite these caveats, it is easy to spot extreme event impacts on yield as illustrated in the figure.

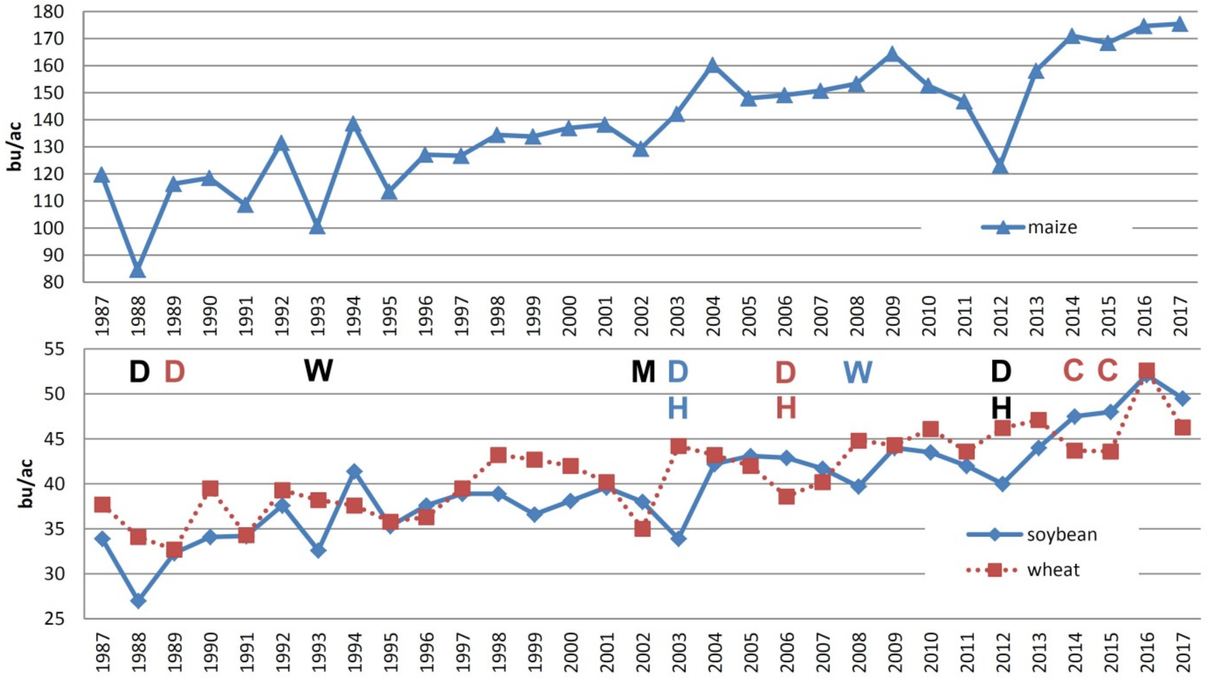

Figure 1. Average annual yields in the U.S. for three major commodities: maize (triangles), soybean (diamonds), and wheat (all types; squares). Letters indicate the primary extreme weather: cold (C), drought (D), heat (H), mixture (M), and wet (W). Letter color black means affects two or more crops, red affects wheat, blue affects soybean. In 1988, drought in the west and midwest US accompanied by hot summer temperatures hammered maize, soybean and spring wheat (Durum yield was down 52%) while winter wheat was largely spared (NASS, 1989). The drought carried over to affect the 1989 winter wheat crop; winter wheat in the central and southern plains was also harmed by extreme cold (NASS, 1990). In 1993, cool and wet conditions delayed planting and maturation of maize and soybean in the 'Corn Belt' with central Iowa fields destroyed by record (once in 500yr) rainfall (NASS, 1994). In 2002, high temperatures disrupted maize pollination in July, while a warm winter followed by unusual May freezes and summer drought led to the lowest wheat acreage harvested since 1917 (NASS, 2003). In 2003, summer drought with high temperatures in the northern growing regions led to a steep decline in soybean yield there; yields elsewhere were much better (NASS, 2004). In 2006, a dry winter reduced winter wheat in the southern plains while a hot summer reduced spring wheat in the northern plains (NASS, 2007). In 2008, a wet spring delayed planting; a dry summer in Ohio plus torrential rains in Louisiana and Texas from two tropical cyclones, reduced soybean yield (NASS, 2009) In 2012, drought and accompanying extreme high summer temperatures greatly reduced yields of maize and soybean but mainly accelerated wheat maturation (NASS, 2013). Drought and higher air temperatures drive plants to transpire and deplete soil moisture more rapidly (Rippey, 2015). Most maize is rainfed; irrigated maize did not have this dip. (e.g. http://farmdocdaily.illinois.edu/2013/04/2012-really-big-one-corn-yields.html) The 2014 and 2015 winters were very cold and dry; those temperatures and lack of snow cover greatly reduced winter wheat with little impact on other wheat (NASS, 2015 and 2016).

2.1 Citrus

Citrus is a tropical or subtropical fruit tree depending on the type of fruit produced. Cold tolerance thresholds vary from kumquats (-8C), mandarins (-6.6C), oranges (-4.4C), grapefruit (-3C), lemon (-1C), and true limes (0C). Florida is the primary growing region for juicing oranges while California is the primary producer of table oranges in the US. Average daily temperatures (Tad) for development are: minimum Tad> 9.4C (49F) to 13C (55F), optimal range being 23-34C (73-93F) and a limiting temperature of 37-39C (Mendel, 1969). However, 6-12 weeks of cold (T<10C) or drought-induced dormancy create a flush of blooms after dormancy ends and therefore synchronizing later fruit ripening. Various combinations of factors that affect bloom efficiency and fruit set are reviewed in Mechlia and Carroll (1989). Citrus needs 90-120cm of water over a year (Critchley et al., 1991).

Low temperatures are a primary limiter of citrus production in the US. Mature trees may tolerate slightly colder temperatures due to cold hardening (see discussion in Mechlia and Carroll, 1989) and the development of larger branches. Damage is caused by ice formation in citrus tissues and not by low temperature specifically; hence combinations of duration and temperature are critical. Fruit damage occurs when the temperature falls below a threshold for at least four hours, though the duration may be less for unripe and smaller fruit. For example: 3-4 hours at -2C (29F) can be worse than a half hour at -4C (25F). In oranges: 4 hours at -7C (20F) kills 1 cm (3/8 inch) or smaller wood, while T< -2C (28F) for 12 continuous hours kills 5cm (2 inch) limbs and possibly the entire tree. A 2007 freeze affecting California caused: $800M losses to the state's citrus industry. Warm weather prior to extreme cold worsens the damage since it promotes a highly cold-susceptible growth flush. Leaf temperature can be 1-2C colder than air temperature on cold, windless, clear nights (e.g. http://aggie-horticulture.tamu.edu/newsletters/hortupdate/2011/mar/citrus_freeze.html) and 2-3C warmer when the ground can radiate heat (bare ground being more effective). Due to the cold sensitivity, growers have ways to extend the temperature range, such as applying water (which releases latent heat as it freezes).

High temperature, especially when coupled with strong solar radiation and low humidity can cause severe wilting, even if there is adequate moisture in the soil. Since transpiration cannot keep leaves cool yield can be affected if the situation persists. Sunscald is also a possibility.

Drought can amplify fruit drop both of young and mature fruit. Water needs vary with temperature and humidity, but in California growing areas, trees need 2-3 gallons per foot of canopy diameter applied each summer day.

Climate conditions can foster some plant diseases: Alternaria brown spot (rain >2mm or wet leaves >10 h, especially for T>20C), Melanose (>10hrs leaf wetness and >24-27C, longer at lower T), Citrus canker (persistent wind-driven, >8m/s, rain with T<35-39C; T=28-30C being optimal; Das, 2003), Greasy spot (relative humidity: RH>90%, especially during summer).

Table 1 Atmospheric conditions that impact citrus production

Variable	Threshold or range	Comment
Growing season (frost free)	>280d	(Hatfield et al., 2008)

Average Daily Temperature (Tad)	Tad~20C (68F); 23C (73F) < Tad < 34C (93F)	Roughly optimal during fruit set (but will set fruit above and below this value); Optimal range during fruit growth
	>26C or <14C; ≥29C	Half of fruit do not set. No fruit set for Tad ≥ 29C (e.g. 32C to 26C diurnal range)
Night minimum temperature (Tmin)	-8C(18F) < Tmin <0C(32F)	Dieback threshold depends on type of fruit, cultivar, duration, previous hardening.
	Tmin >13C (55F)	Minimum for adequate fruit set
maximum temperature (Tmax)	36/31C day/night range	Pollination fails.
	Tmax >35C (95F)	Yields decline in navel oranges, about 3C higher for valencias
	Tmax >40C (104F)	Plant may wilt (with strong solar radiation) even with adequate soil moisture
Duration of wet leaf surface + air temperature (T)	>10h + T>20C(68F)	Some foliar diseases amplified
Precipitation	Drought	Heat during drought (or when irrigation withheld) can cause fruit drop, even tree mortality
	Excessive	Skin splitting & rot. Some foliar and root diseases promoted.

2.2 Dairy and Beef Cattle

Beef cattle are widely dispersed across the U.S. while dairy production is more concentrated in California, Wisconsin and the Northeastern States (Hatfield et al., 2014). Together, beef and dairy account for more than a quarter of all the agricultural value in the U.S. There are ~1.8M dairy cows in California, the leading state for dairy production, with many cows populating the southern San Joaquin valley. This region is characterized by hot, dry summers, so heat stress is a significant concern. Heat stress causes a cow to go off feed which leads to no milk production. During the 2006 heat wave and for weeks after, milk production suffered totaling >$95M in losses. There was 10% mortality in that region during the event (30,000 cows died) in part because the temperatures did not cool sufficiently at night and cows could not recover from extreme daytime temperatures.

Being mammals, it is important for cattle to maintain a core temperature in a narrow range. For example, cattle on a range can seek available shade when hot, sun when cold. Generally, a combination of variables in their environment is important in determining what weather is extreme for the animal. A common metric that combines temperature and relative humidity stress is the temperature-humidity index (THI).

$$\mathrm{THI} = (0.8 \times T) + [(\%\ \mathrm{RH}/100) \times (T - 14.4)] + 46.4.$$

THI is adapted from the discomfort index (Thom, 1959) which uses wet and dry bulb air temperatures. It is clear that THI increases if relative humidity is high. (The animal is less able to cool by panting.) THI is most relevant for heat stress. THI is used to define the associated livestock weather safety index (LWSI). Mader et al. (2010) define a metric: CCI that includes relative humidity (RH), wind speed (WS), and direct solar radiation (SR) modifications to the air temperature (T). CCI has a complex formulation illustrated best by examples. CCI ranges from -44.1 (T = −30°C, WS = 9 m/s, SR = 100 W/m2, and RH= 80%) to 67.7 (T = 45°C, WS = 1 m/s, SR = 900 W/m2, and RH = 80%) An example where hot conditions would be considered severe is: CCI = 37.9, from T = 30°C, RH = 50%, WS = 1.0 m/s, and SR = 500 W/m2. CCI is more broadly applicable than THI by assessing cold conditions. For dairy cattle, T=20-22C optimal; productivity declines ~2% for each 1C above 22C.

Excessive cold is capable of causing death for unsheltered animals when < -5 CCI for young or nonacclimated animals or < -20 CCI for animals that have acclimated to cold (Mader et al., 2010).

As mentioned, excessive heat in combination with high humidity creates high stress. THI values between 74 and 79 are considered dangerous, with values above 84 indicating an emergency situation (Amundson et al., 2006). Anything above 84 (the high threshold) is considered highly stressful conditions. THI >90 (e.g. T=45C, RH=25%) leads to a 20% drop in milk production, aborted fetuses, and the reproductive cycle interrupted for weeks afterward. Other work (Bilby et al., 2008) finds lactating cows to have >1C higher core temperatures than heifers for ambient air temperatures above 30C. A THI value exceeding 98 is considered ‘fatal’ to cows but this ignores other factors like duration above thresholds and solar radiation (and coat color; Gaughan et al., 2009) which amplify the problem or wind which can reduce the problem (e.g. Mader et al., 2010). Considering duration, THI is often interpreted in terms of hours times degrees above the threshold (Hahn, et al., 2009) like THI=84; the purpose being to estimate the core temperature of the animal. As little as 3 THI-hours/day for 3 days (Hahn et al., 1999) is considered severe if nighttime THI values do not dip below 72 for more than two hours. More recently other metrics, such as black globe temperature, that include more factors have been developed (see Mader et al., 2010 for a review).

Table 2 Atmospheric conditions that impact beef and dairy production

Variable	Threshold or range	Comment
Daily average temperature (Tad)	Tad>22C	Milk productivity declines 2% for each 1C above this threshold
Minimum CCI (see text)	CCI < -5	Mortal cold conditions for young cattle. E.g. T= 5C, RH=80%, WS=9m/s,

		SR=100W/m^2
	CCI < -20	Mortal cold for acclimated cattle. E.g. T= -10C, RH=20%, WS=9m/s, SR=100W/m^2
Day maximum THI	THI<74; 75≤THI<78; 79≤THI<84; 84≤THI<98; THI>98	‘normal’; ‘alert’; ‘danger’; ‘emergency’; ‘fatal’ labels for these conditions are commonly used (e.g. Hahn et al., 2009) and defined from cattle transport experience (LCI, 1970)
Daily THI-hours (THI-hrs)	3/day≤THI-hrs≤15/day; 15/day≤THI-hrs≤30/day	Severe; extreme conditions if lasting 3 or more days with 0 to 2 hours of THI<73 each day.

2.3 Field Fruits (strawberries and cucurbits)

Commercial strawberries are an herbaceous, perennial, subtropical plant. As such, about 80% of the crop by weight is grown in California in two primary regions, depending on the time of year. Much of the remaining U.S. production is in Florida. Strawberries like cool conditions; ideal temperatures are 13-21C (55-70F). The plant is positively correlated with solar radiation and temperature, so if temperatures were to become uniformly warmer over a year, there would be earlier fruiting but less overall yield (Palencia et al., 2013).

Minimum temperatures are a concern. Strawberries are most sensitive to frosts and freezes, when Tmin <0C or when the leaf or flower surface temperature drops below 0C, during and just after bloom. Mature fruit tolerate 1-2 C colder. If cooling is gradual, plants may tolerate Tmin of -6C (21F). A cold air outbreak in January 2007 caused $41M in strawberry losses.

Maximum temperatures can be too warm for strawberries. Productivity drops when air temperature exceeds 24C (75F) with fruiting stopped for day-neutral strawberries above 29C.

Other concerns include: wind accompanied by low RH; such as during ‘Diablo’ and ‘Santa Ana’ winds. The combination can desiccate the fruit. Hail is rare in the main California strawberry growing regions but when it happens it is highly damaging. Cold, rain, high wind, and prolonged cloud cover all inhibit bee pollination.

Strawberry pests (Westerlund, et al., 1999) include: corn earworm (*Heliothis zea*) whose generations are accelerated by higher temperatures (T). Saltmarsh caterpillar (*Estigmene acrea*) is more problematic during hot conditions. Diseases and other pests affected by high RH (with T factor): *Botrytis* fruit rot (cool T), *Rhizopus* fruit rot (T>8C), powdery mildew (T>15C), *Mucor* fruit rot (high T; some species not inhibited by cold). Wet conditions: *Anthracnose*, Garden *Sympgylan*, *Phytophthora* species (cool soil), Angular leaf spot (daytime T~20C).

Cucurbits include watermelon, cantaloupe, honeydew, cucumbers, and squashes. These annual plants are vining and tropical so they are sensitive to cold at any growth stage. The plant tissues are destroyed by freezing temperatures. The plants are bee pollinated, so rain and cool temperatures can inhibit bee flight.

The optimal temperatures for melons are higher than for strawberries. Optimal ranges are 30-35C for cantaloupes and 21-29C for watermelons. The maximum temperature that plants can tolerate is also higher, up to 45C (113F) for muskmelon (Baker and Reddy, 2001) but 32C (90F) for watermelon (Elwakil et al., 2017). The plants require 25-38cm of water, so drought (or insufficient irrigation) can significantly reduce yield as can water applied a week before harvest (Hartz et al., 2008).

Squashes tolerate daily mean temperatures of 18-27C (64-80F). Tmin=16-21C with Tmax=24-29C are optimal ranges. Temperatures below 4C injure squash and cucumbers while temperatures above 29C cause flowers and undersized fruit to drop. Squash and cucumbers are thirsty, requiring 2.5cm water/week in Florida (Mossler and Nesheim, 2014)

Table 3 Atmospheric conditions that impact strawberry production

Variable	Threshold or range	Comment
Growing season (frost free)	~100d	(Hatfield et al., 2008)
Night minimum T (Tmin)	Tmin ≥ -6C(18F); 0C(32F); -2C(28F)	Thresholds for: plant survival; blossom pollination and nascent fruit survival; mature fruit survival
Day maximum T (Tmax)	Tmax >24C (75F); 29C (84F)	Fruiting declines; stops
Relative humidity (RH)	High values	Foster certain pests and diseases in various T ranges.
	Low values	Fruit may desiccate
Thermal conditions that impact melon production		
Growing season (frost free)	~110d; 65 to >90d	Winter types (e.g. honeydew); summer types (e.g. watermelon)
Night minimum T (Tmin)	Tmin ≤0C(32F)	Tissues freeze
Temperature (T)	T <16C (60F)	very slow growth below this threshold for muskmelon.
Soil temperature Tsoil	Tsoil <21C (70F)	slow growth below this threshold for watermelon
Day maximum T (Tmax)	Tmax >41-45C(106-113F); >32C (90F)	Critical temperature threshold for muskmelon; watermelon (Florida)
Atmospheric conditions that impact cucumber and squash production		

Night minimum T (Tmin)	Tmin ≤0C(32F); 4.4C(40F)	Tissue quickly destroyed; plant production halted if cool T persists several days
Day maximum T (Tmax)	Tmax>29C	Blossom and small fruit drop

2.4 Field Vegetables (carrot, cole, lettuce, potato, spinach)

Many vegetables are grown as annual row crops. A sampling of economically larger commodities is considered here. Leaf crops, Cole crops, and other vegetables are generally very sensitive to extremes: during seedling establishment (hot or cold: spring or early fall) and during pollination (frost or high heat for crops sold as fruits). Optimal and max temperatures are cool: (12-24C/ 24-35C, respectively). Hatfield et al. (2008) tabulate ranges for germination, optimal yield, and growth for several field vegetables.

Leafy vegetables include lettuce and spinach. For low values of Tmin and Tmax, plant development is slow. An optimal daily temperature range is Tmax ~23C (73F) and Tmin ~7C (45F). Freezing causes damage of outer leaves making the plant more susceptible to diseases. Lettuce is generally sensitive to high temperatures though there is some variation between varieties. For iceberg lettuce temperatures >25C (77F) accompanied by >8 hours sunlight cause early bolting (flower stalk and seed production) before the head has reached full size. Iceberg lettuce is grown where nighttime temperatures are 3-12C and daytime temperatures 17-28C (Turini et al., 2011). Germination is optimal for 20-25C but inhibited or impossible above 30C (Ryder, 1997) without priming. Lettuce requires a lot of water (~1m for iceberg; less for leaf lettuce) over the crop cycle with 1.5 to 3 times this amount applied depending on the irrigation method (Turini et al., 2011). Spinach can tolerate a wider range of temperatures than lettuce. Spinach seeds geminate between 2-30C, though 7-24C is optimal (Koike et al., 2011). Temperatures of 15-18C produce optimal growth though there is some growth down to 5C and up to 30C. However, bolting is prompted by longer day lengths and temperatures above 23C. Mature spinach plants survive temperatures down to -9C (Koike et al., 2011). The water needs are 1/4 to 1/3 those of lettuce varieties.

Broccoli tolerates a wider range of temperatures than cauliflower. Broccoli seeds geminate between 4-35C, though 7-24C is optimal (Koike et al., 2009). Mean temperatures of 18-20C produce optimal growth. Broccoli (cauliflower) will grow with temperatures from 4-35C (3-29C) though growth slows outside the optimal range (LeStrange et al., 2010). For temperatures ≥27C, cauliflower heads develop undesirable properties. Frost damages seedling and young plants; mature plants can tolerate temperatures to -5C. The water needs are similar to those of iceberg lettuce, though cauliflower needs more water applied than broccoli.

Potato tolerates higher temperatures than carrots. Potato plants are thought of as preferring cool conditions (18-21C), but they can tolerate high temperatures (e.g. 38C, 100F) if nights are cool (e.g. 18C; Rosen, 2010). Without cool nights, 30C is considered a maximum tolerated temperature. Soil temperature should be at least 4C, 10-21C is optimal, and for 22-35C growth is possible. Potatoes tolerate slightly colder temperatures (-1C, 30F) than their relative, tomatoes, with increasing damage (dependent on duration) for colder temperatures, though -3C (26F) is an effective limit. Some varieties of potato can tolerate colder conditions or acclimate to them, but not all (Oufir et al., 2008). Potatoes need about 2.5cm/week during the latter stages of tuber formation. Schafleitner et al. (2011) describe a wide variation in drought tolerance among potato varieties.

Carrot foliage tolerates some frost, however, below 10C air temperatures foliage and root grow slowly. Optimal taste and color develop for temperatures between 18-21C (or daily average temperatures from 15.5-18C); undesired flavors develop for air temperatures above 30C (Nuñez et al., 2008). Seeds can germinate in soil temperatures from 4C to 35C, but optimally from 15-29C.

Table 4 Atmospheric conditions that impact lettuce and spinach production

Variable	Threshold or range	Comment
Night minimum T (Tmin)	Tmin >0C (32F); Tmin ≥ -9 to -5C(16-23F)	Damage to: lettuce and seedling spinach; (mature) spinach
Day maximum T (Tmax)	Tmax>25C (77F); Tmax ≥30C (85F)	Growth stops for: lettuce; spinach
Daylength	>14 hours (with T>23-24C)	Accompanying mild or warmer temperatures leads to bolting
Atmospheric conditions that impact other cole crops production		
Night minimum T (Tmin)	Tmin >0C(32F); -7C(20F)	Seedling; mature plants damage thresholds
Day maximum T (Tmax)	Tmax ≥27C; 35C	Cauliflower; broccoli stop growing
Thermal conditions that impact carrot and potato production		
Growing season (frost free)	75-90 to 135-160d; 30-40 to 50-80d	Early season to late season potatoes (varies with cultivar); baby to mature carrots (varies with cultivar)
Night minimum T (Tmin)	Tmin >-2C(30F); > -1C (30F)	Threshold to avoid carrot; potato foliage damage
Soil temperature (Tsoil)	4C ≤ Tsoil ≤35C	Carrot germination or potato sprouting do not occur outside this range
Day maximum T (Tmax)	Tmax >29C; 35C	Carrot; potato plant quality thresholds

2.5 Grapes

Grapes are a temperate climate perennial vine subdivided into three production categories: table grapes, raisins, wine grapes. Wine grapes are grown from cool growing season average temperature: Tgsa =13C (55F) to warm: Tgsa=21C (70F) climates. Table grapes are grown from warm (Tgsa= 17C; 63F) to hot (Tgsa=22C; 72F) conditions, while raisins are grown where drying is fostered at hot Tgsa conditions (≥20C; 68F) from Jones (2005). Table grapes include muscadines which are adapted to southeastern US conditions and concord which is adapted to the US northeast. In terms of diurnal range, plant leaves do well for daytime temperatures from 20C to 32C (Ferrini et al, 1995). Sunny warm days (optimally 27C) promote the vine's physiological processes, sugar content, and ripening while cool nights retain acidity which are primary characteristics manipulated by a winemaker.

Grapes need a period of winter dormancy with temperatures below 10C, though 7C is the usual threshold for calculating chilling hours (CH). CH accumulates hours between 0-7C but the sum may be reset to zero by several days where temperatures remain above 7C. Most varieties of grapes only need CH=50-400 h (100-150 h for most commercial varieties) but some wild varieties require CH>4000 h. Higher values of CH are desired (750 h is typically quoted) to improve the synchronization of bud break once temperatures are sustained above 10C.

Grapes become physiologically active for T>50F (Williams et al., 1985). Flowering needs daily average temperatures between 17 and 20C. Cooler temperatures delay bud break and development (pushing the growing season into unfavorable late fall weeks). Grapes are adapted to a wide range of climates, so the heat accumulation needed varies from 1700 degree days up to more than 4000.

Freezes (T< -2C) are most problematic during flowering through nascent fruit formation or late in the season near harvest. European varieties generally have less cold tolerance and CH than American varieties. A warm period (day + night average T>5-10C) pushes bud break making a following frost devastating.

High temperatures impede grape development, where this is often expressed by two thresholds: reductions start for Tmax >35C and become extreme for Tmax ≥40C. For example, when Semillon grapevines were exposed to a simulated heat wave, Tmax=40C, Tmin=25C at different growth stages, growth stopped during veraison (development of grape color) and mid-ripening, taking a dozen days to recover (Greer and Weston, 2010). Thompson seedless (Matsui et al., 1986) table grapes respond similarly. Veraison is reduced for daytime temperatures above 25C while Tmax>32-36C effectively stops coloring for Pinot Noir, Cardinal, and Merlot (Spayd, et al., 2002) wine grapes. Timing relative to mid-season thinning matters; an extreme heat wave in July helped make up time lost by delayed bud break of the cool spring during 2006 in California. Hot and dry conditions near harvest, especially when accompanied by wind (e.g. ‘Diablo’ and ‘Santa Ana’ winds) can dry wine grapes like raisins, cause sunburn, and shrink harvest period, as happened in 2008. Red wine grapes at high temperatures (T=35/20C during daytime/nighttime hours) have half the anthocyanin pigments as those grown at 25/20C and hence lowered fruit quality (Mori et al., 2007).

Precipitation has multiple effects. Too much rain in spring disrupts regular deficit irrigation resulting in too much plant growth. Rain during pollination inhibits fruit set (such conditions reduced fruit set in California by 25% in 1996). After a prolonged dry spell, rain near harvest can cause berries to crack and burst. After harvest, rain disrupts raisin drying in the field. *Vitus vinifera* or *V. labrusca* have too many disease problems where summer temperatures and humidity are high though less desirable muscadine grapes are so adapted. Grapes need roughly 25-75cm of water over a season (implying 90-120cm of irrigation) but the amount needed is not even. Most of the water demand (~70% of the total) is from fruit set to harvest.

Table 5 Atmospheric conditions that impact grape production (all types)

Variable	Threshold or range	Comment
Chilling hours (below 7C or between 0-7C)	>100; >750h	For winter dormancy of most *vinifera* varieties; for good bud break synchrony
Growing season (frost free)	~100d; >120d	American; European. (Hatfield et al., 2008)
Average daily temperature over growing season (Tgsa)	Tgsa >20C (68F); >22C (72F)	Fruit quality reduced for wine grapes; table and raisin grapes
	Tgsa =10C (50F)	Threshold to break dormancy, base temperature for growing degree days
Night minimum T (Tmin)	Tmin > -20C(-4F) to -5C (23F)	Tolerated when plant is dormant, varies widely between species and with winter conditions. Some wild types tolerate -40C
	Tmin <0C (32F); -2C (28F)	Damages new growth; significant yield reduction, grapes may freeze and burst depending on duration of cold
Day maximum T (Tmax)	Tmax >35C (95F)	Yields decline in many varieties during veraison and ripening. Red types may not develop full color.
	Tmax ≥40C (104F)	Yields decline in many varieties of wine and table grapes
Wind (W) + low relative humidity (RH)	W>5m/s with RH<30%	Fruit desiccation
Precipitation (P)	Drought: P < ~50cm/growing season	Plants need most moisture from fruit set to harvest
	Excessive	Depending on timing: Inhibits pollination. Some foliar and root diseases promoted. Mature fruit skin split and rot if after drought.

2.6 Maize

Maize (or ‘corn’) is a tropical annual grass that produces unusually large and abundant grain. Maize holds the number one value and tonnage of US crops and livestock feed. While widely grown, most maize is produced in the ‘Corn Belt’ region from the northern Ohio River valley across to the northern high plains (Hatfield et al., 2014). The acceptable germination, growth ranges, and optimal growing range of average daily temperatures (Tad) are 16-35C, 12-35C, and 20-25C, respectively (Hatfield et al., 2008). Maize needs 50-80cm of water per 80-110d growing season (Critchley et al., 1991) while 64 cm (Schlenker and Roberts, 2009) optimizes yield. However, where maize is grown in hotter climates 80-130cm are needed (Ouda et al., 2016)

Being of tropical origin, maize is sensitive to minimum temperatures near freezing. While the plant is damaged by temperatures between -2 to 0C, the plant might actually survive; temperatures below -2C will kill the plant (Nielsen and Christmas, 2002). Germination depends on soil temperature, with 10C often quoted as a minimum threshold (e.g. Silva, 2013). There is wide variation in cold tolerance dependent on moisture content and variety, but none survive -10C (Harper, 1956). For example, Hund et al. (2008) find significant differences in development between maize lines for a 2C reduction in temperature (Tmax/Tmin of 15/13C vs 17/13C). Cold periods can foster diseases (e.g. Elmore and Doupnik, 1995).

Increasing temperature shortens the period of grain-filling which leads to smaller grains and yield (Badu-Apraku et al., 1983). While maize survives brief Tmax>45C with adequate soil moisture, such high temperatures cause lasting yield decline. Schlenker and Roberts (2009) find that yields increase up to a critical temperature (Tc=29C) above which yield rapidly declines as temperature increases but at a nonlinear rate. (E.g. replacing one day at 29C with 40C causes a 7% declines in yield.) Herrero and Johnson (1980) and Dupuis and Dumas (1990) conclude that pollen loses viability at temperatures above 38C and 36C, respectively. Dupuis and Dumas specifically show no fertilization when exposed to four hours at 40C. Commuri and Jones (2001) show that kernel development rate rapidly declines for temperatures rising from 30C to 35. Cheikh and Jones (1994) show that mismatched hormonal changes in the kernels in the 10-12 days after pollination occur for four days of sustained Tad=35C.However, plant vegetative growth tolerates temperatures a few degrees higher, declining only for Tad> 38C (Crafts-Brandner and Salvucci, 2002). Commuri and Jones show that a night/day temperature range of 35/40C had less than half the yield of a 20/25C range. Hatfield et al. (2008) estimate a ‘failure point temperature’ of 35C based on averaging prior studies, including the temperature effects at endosperm division stage. Teixeira et al. (2013) estimate a threshold for damage (Tcrit) and for ‘maximum impact’ (Tlim) for daytime temperatures of Tcrit/Tlim = 35/45C. Deryng et al. (2014) note that estimates vary for Tcrit (30-35C) and Tlim (40-45C). Critical and limiting temperatures have large or small impact depending on the development stage of the plant.

Much of the U.S. ‘corn belt’ is rainfed agriculture. When grown as rainfed, too little rainfall can affect growth (e.g. Lobell, et al., 2013). High heat is often associated with drought (e.g. De Boeck et al., 2010). Runge (1968) used a 54 year record from Illinois to estimate the effects on yield of 2.5cm less rain than normal for every 2.8C increase in temperature above normal at different dates before and after anthesis (flowering). Runge found the effect to vary (positive or negative yield changes) depending on when the drought or high temperatures occurred. For maximum temperatures above 29C, yield declined no matter when the rainfall deficit of 2.5cm occurred. Westgate and Hatfield (2011) summarize the effect as P<4.5cm/8d created 1.2-3.2% decline in yield for each 1C rise in Tmax; similarly, for Tmax=35C, each 2.5cm decline in P reduced yield by 9%. However, the timing matters greatly. Runge showed higher declines in yield for these Tmax or P anomalies happen from 5 weeks before to 2 weeks after flowering with the biggest decline about two weeks before flowering. There was not a critical threshold identified, though Tmax of 40.6C could cause a 14% decline from normal for a 2.5cm drought.

Excessive rainfall (>1m in the growing season; Takle et al., 2013) can foster pathogens, stunt growth (due to saturated soils), cause erosion, and/or inhibit mechanical operations at critical times (e.g. at harvest). Examples of heat and drought in 2003 and excessive wet in 2007 over France are discussed in van der Velde et al. (2012). In flooding conditions, plants can survive submergence about two to days if conditions are warm, up to four days if temperatures are cool (Ritchie et al., 1997).

Hail can also damage crops, though each event usually does not cover a large area (e.g. Omoto and Seino, 1978). Changnon. (1971) finds a minimum hailstone diameter of 6.4mm causes damage to maize with the fraction of crop loss being higher in summer (June-August) than in May for a given number of hailstones. While the plant may survive, injury to the growing point may result in abnormal growth and a total loss (e.g. Johnson, 1978).

Table 6 Conditions that impact maize production

Variable	Threshold or range	Comment
Soil Temperature (Tsoil)	Tsoil≥10C	Minimum threshold for seed germination
Growing season (frost free)	~65 to 120d	Varies with cultivar
Low Average Daily Temperature (Tad)	0C(32F) < Tad <10C(50F)	Growth slowed, some pathogens enhanced, yield declines rapidly for colder Tad
High Tad	Tad >29-35C (84-95F)	Yields decline depending on plant growth stage timing (2 weeks before flowering most sensitive) (Tcrit)
	Tad >40-45C (104-113F)	Crop failure (Tlim)
Night minimum T (Tmin)	Tmin <0C (32F); -2C (28F)	Damages new growth; kills young plants. (some varieties tolerate even colder, but none survive -10C)
Day maximum T (Tmax)	Tmax >40-45C (104-113F)	Heat stress maximized
Precipitation (P)	Drought: P < 4.5cm/8d	Yield declines. Effect amplified by Tad above optimal range
	Excessive P >100cm/growing season (except where hot, soil well drained, etc.)	Fosters pathogens. Flooding survived if <4 days (at T~18C) or <2 days (at T~24C)
Hail size	Size >6.4mm	Leaf destruction, higher % loss later than earlier in growing season

2.7 Nursery and Greenhouse

Nursery and greenhouse operations had $16B in cash receipts in 2009. Greenhouses are operated to be within the middle 95% of the ranges of growing requirements for the plants being housed. Greenhouse growers manipulate the temperature range Tmax-Tmin to adjust crop development for marketing purposes (e.g. for 'Easter' lilies to start blooming just before Easter Sunday). Such timing can be disrupted by extreme events.

Outdoor nurseries are somewhat controlled environments where some protective measures can be taken to protect frost-sensitive plants. Typically, such measures protect to a Tmin of -2C (28F). However, cosmetic damage can be costly. The January 2007 freeze caused $161M in nursery losses in California. While T> -2C is often workable, sometimes the latent heat release from overhead sprays can protect for temperatures down to as low as -3C (25F). Cold damage is amplified when a preceding warm period spurs a flush of highly sensitive new foliage. Air temperatures below -3C (25F) is a threshold generally used to indicate total loss of frost-sensitive crops.

Extremely high temperatures can also be damaging. Generally, sustained Tmax>90F is a threshold for foliage/yield loss, while several hours above 100F are often deadly. The root ball is hard to keep cool in potted plants since it is exposed on the sides and often the root ball is too small for the foliage (causing excessive evapotranspiration). The situation is worsened by low humidity (30<RH<40% taxes plant; RH<20% is severe). If windy, overhead evaporative cooling spray may miss plants. Commonly, greenhouses use evaporative cooling maintaining up to 20F cooler than outside, but effectiveness declines for higher ambient relative humidity.

Other hazards include structure damage. Strong winds can cause glass breakage or plastic cover tearing, exposing plants to undesired conditions. This is separate from wind load which depends on greenhouse shape, size, height, winds, etc. The National Greenhouse Manufacturers Association (NGMA) specifies design plans use winds of at least 31m/s (70 mph). Accumulations of snow can collapse shade or lathe houses as well as greenhouses. NGMA minimums are based on lbs/ft^2 and vary with the local climate. Hail can break greenhouse rigid panels (glass or plastic) or puncture plastic. Outside, hail causes plant trauma. In May 2011 a hail storm causes a 30% loss of bedding plants in Sacramento California.

Table 7 Atmospheric conditions that impact nursery and greenhouse production

Variable	Threshold or range	Comment
Night minimum T (Tmin)	Tmin > -2C(-28F) to -3C(25F)	Some effectiveness of broad protective measures on frost-sensitive plants
	Tmin < -3C (26F)	Protection fails for frost sensitive plants
Day maximum T (Tmax)	Tmax >32C (90F); >38C (100F)	Threshold for foliage/yield loss; threshold for severe losses
Wind (W)	Varies; > 31-36m/s (70-80mph)	Wind load that exceeds structure design parameters varies; NGMA minimums

Hail and snow	varies	Different coverings and framing offer different levels of protection.

2.8 Rice

Rice is a major grain crop requiring a long frost-free period to develop. Arkansas is the primary producer of this annual grass in the US and California is second. With many cultivars suited to a range of tastes and climates, the sensitivity to temperatures varies markedly with cultivars, but some broad generalizations follow. The temperature range for rice growth is 10C <T<37C (no growth outside this range). Rice needs 100-110cm of water per 90-150d growing season (e.g. Henry et al., 2016); however, where rice is grown in hotter climates 15% more water is needed (Ouda et al., 2016).

Rice needs minimum temperatures Tmin> 20C (68F). Below Tmin of 20C the percentage of blanks increases (from 12 to 50%) 60-75d after planting (early into ‘heading’). Also, cooler temperatures slow maturation, push harvest into windier, cooler late autumn. Two weeks before heading (when the panicle becomes visible, late July in California) if Tmin drops below 20C for 3 nights in a row, the subsequent flowering will suffer cold-induced sterility.

Conditions can be too hot for rice. Grain-filling (after flowering) declines for cool nighttime temperatures, ideally 25C< Tmin <33C. There is a 10% decline for each 1C above 33C. Rice is most sensitive during pollination. Heat tolerance varies with rice genotype (Jagadish et al., 2008). Fertility can be dramatically different (Satake and Yoshida, 1978) if it is hot during the short period (a few hours) during which fertilization occurs with high temperatures Tmax ≥ 38-41C (depending on duration) causing near sterility in most commercial cultivars. Boote et al. (2013) conclude that fertility declines for Tmax>32C. Teixeira et al. (2013) indicate average daily critical and limiting temperatures of 35C and 45C which is higher than other studies that find Tlim of 38C (Baker et al., 1995) or 36-40C (review by Hatfield et al., 2011).

Drought can inhibit any phase, but drought early in the grain formation has lasting impact. Excessive precipitation during spring planting can disrupt sowing (as happened during 2011 in California).

The biggest problem created by high relative humidity (RH>50%) is foliar diseases, common in the south-central US rice belt. Low humidity is more commonly a problem in California. Cracking occurs if the diurnal range is too low at harvest. This problem may arise from a combination of wind and RH range. The rice grain dries during daytime then rehydrates at night. However, if rice dries out too much during the hot part of the day (down to 16% moisture content, say) then reabsorbs water during the higher nighttime humidity (back to say, >20%), then the seed cracks. When milled, that cracked seed shatters and is lost; the farmer is paid for whole seed, not shattered bits.

High wind speeds (WS>20m/s) can be associated with multiple problems. Wind may cause extensive lodging (grain stalks blow onto the ground) during harvest (after field water removal). Wind can often be accompanied by low RH (does not reach 90% at head height). In October 2004, the rice growing region of California experienced WS>40 kph with gusts >70kph, the daytime RH dipped to 13%, and for 4 days there were no hours with RH>90%. The result was head yields dropped 50%.

Table 8 Atmospheric conditions that impact rice production

Variable	Threshold or range	Comment
Growing season (frost free)	90-150d	(Henry et al., 2016)
Temperature (T)	10C (50F) < T < 37C (98F)	Little or no growth outside this range
High average daily T (Tad)	Tcrit >35C (95F)	Critical temperature (Tcrit). Yields decline (depending on plant growth stage timing).
	Tlim >36-40C (113F)	Crop failure temperature (Tlim) outside of flowering. Tlim=33C if occurs during flowering.
Night minimum T (Tmin)	Tmin <20C (68F)	Cold sterility during heading (60-75 days after seedling planting)
	25C < Tmin < 33C	Grain filling (from 58-92 days until 100-150 days after seedling emergence) declines if too warm, declines by 10% for each 1C above 33C
Day maximum T (Tmax)	Tmax >32C(90F); 38-41C (100-106F)	Pollination disrupted (58-92 days after seedling emergence); sterility threshold
	Tmax < 10C (50F)	Ripening (after grain filling) greatly inhibited
Relative humidity (RH)	RH >50% (with warm T)	Foliar diseases amplify for sustained high RH with warm to hot temperatures
	RH <20%	Seed can crack, then shatter during harvest or processing
Wind speed (WS)	WS >20 m/s	Can blow down crop, may be accompanied by very low RH

2.9 Soybean

Soybean is an annual legume cultivated in a similar region of the US as corn; in terms of US crop value it ranks number two; in terms of US crops and livestock tonnage it ranks third.

Widely planted, it is most concentrated in nearly the same region as the ‘Corn Belt’ (e.g. Hatfield et al., 2014). The growth range is average daily temperature (Tad) of 12-40C with better production for Tad=23-32C, where the Tad was based on a 10C diurnal range between Tmax and Tmin (Boote et al., 2005). Vegetative growth (e.g. leaf area index) increases but photosynthetic rate is essentially constant for air temperatures of 26, 31, and 36C (Campbell et al., 1990). Boote et al. (2005) find the optimal harvest index near Tad=26C corresponding to Tmax/Tmin=32/22C though seed size declined for Tad>22C. Other studies (Sionit et al., 1978; Boote, 2008) find Tad near 23C (Tmax/Tmin=26/20C) for optimal yield. Hence, Hatfield et al. (2008) state the optimal Tad during reproductive growth for grain yield to be 22-24C. Soybean needs 45-70cm of water per growing season (Critchley et al., 1991) while 69 cm (Schlenker and Roberts, 2009) optimizes yield.

The plant transition from vegetative growth to flowering is strongly tied to day length, so during summer, anthesis occurs first in the northern states and up to a month later in southern states (Schapaugh, 2016)

Cold temperatures at or below -2C kill soybeans; frost at higher temperatures causes damage (Nielsen and Christmas, 2002). There is no vegetative growth for Tad below 6C prior to flowering (Grimm et al., 1993). Pollination fails below 13C (Salem et al., 2007). Seeds risk chilling injury for soil temperatures below 16C while germination fails due to imbibition (swelling by liquid water uptake) with soil temperatures less than 5C (e.g. Leopold, 1980).

Soybean is more tolerant than rice of high temperatures. Vegetative growth is not limited by temperature as much as seed formation is (Boote, 2008). Pollen viability declines for (instantaneous) temperatures >30C to fail at 47C (Salem et al., 2007). Yield declines rapidly for average daily temperatures (Tad) above 32C (i.e. Tmax/Tmin=36/26C) leading to declining productivity until reaching crop failure for Tad=40C (i.e. Tmax/Tmin >44/34C; Boote et al., 2005). Schlenker and Roberts (2009) find that yields increase up to a critical temperature (Tcrit=30C) above which yield rapidly declines as temperature increases but at a nonlinear rate. Estimates of critical and limiting average daily temperatures agree well: Tcrit=35C and Tlim=40C in (Teixeira et al., 2013) and 34-35C and 40C respectively in Deryng et al. (2014). Boote et al (2013) indicate a Tcrit of 39-40C.

While precipitation of 69cm may optimize yield, the plants use water most rapidly during the reproductive stages, especially from full bloom to pod filling stages (Jasa, 2003) reaching 8mm/d for example, in Kansas growing conditions (Rogers, 2016). Excessive precipitation may cause excessive vegetative growth and lodging (laying on the ground). In flooding conditions, plants can survive submergence for 2-4 days (Scott et al., 1989; Sullivan et al., 2001) though young plants submerged in warm conditions are more at risk. Disease pressure increases with time under water

Changnon. (1971) finds hailstones >6.4mm diameter cause more damage to soybean in early summer (May-June) than later (July-August) for a given number of, or impact energy from, hailstones. Damage before and during the first two weeks of flowering can be mitigated by the plant developing new flowers.

Table 9 Conditions that impact soybean production

Variable	Threshold or range	Comment
Growing season (frost free)	135-150d	(Critchley et al., 1991)
Soil Temperature (Tsoil)	Tsoil ≥4.5C (40F); Tsoil ≥10C(50F)	Minimum thresholds: for any seed germination; for full germination possible
Low Average Daily Temperature (Tad)	0C(32F) < Tad <10C(50F)	Growth slowed yield declines rapidly for colder Tad
High Tad	Tad >34-35C (93-95F)	Yields decline depending on plant growth stage timing (Tcrit)
	Tad >39-40C (102-104F)	Crop failure temperature (Tlim)
Night minimum T (Tmin)	Tmin <0C (32F); -2C (28F)	Damages new growth; kills young plants.
Precipitation (P)	Drought: P < 7.5cm/10d	Yields decline most strongly during pod formation and elongation. Effect amplified by Tad above optimal range
	flooding	Fosters pathogens. Flooding survived if <4 days (at T~18C) or <2 days (at T~24C)
Hail size	Size >6.4mm	Leaf destruction, higher % loss in spring

2.10 Tomatoes

Tomatoes are a tropical vining plant. California leads the nation in production of processing tomatoes (https://www.cdfa.ca.gov/Statistics/PDFs/2016Report.pdf). Due to the annual summer drought, commercial tomatoes grown in California are irrigated with buried drip being the most common (78% in 2012; http://apps.cdfa.ca.gov/frep/docs/Tomato_Production_CA.pdf) irrigation method. Plants can be determinate (one set of fruit) or indeterminate (continuing production of fruit) with the earliest varieties yielding ripe fruit in as few as 55d.

Being tropical, the plant is adversely affected by low temperatures. Plants are frost sensitive. A light frost can cause leaf defoliation. Even when temperatures are a few degrees above freezing, clear nighttime skies and light winds can cause leaf temperatures to become cold enough to be damaged. Soil temperature needs to be warm enough for seeds to germinate and for the plant to have vigor; greater than about 20C is required for soil germination. However, transplants are now common, exceeding 30% of all acreage in California. The combination of cool soil and air temperatures promotes *Verticillium* wilt (http://ipm.ucanr.edu/PMG/r783100911.html). The plant needs minimum temperatures (Tmin) to stay above 13C (55F) for fruit to set.

Tomatoes have high temperature limitations. Plants suspend forming new fruits or abort development of nascent fruits at high maximum temperatures (Tmax). Pollination fails for Tmax>40C though the plant survives with adequate water. Optimal daytime maxima fall in this range: 24C< Tmax <34C (https://anrcatalog.ucanr.edu/pdf/7228.pdf). In terms of daily average temperatures (Tad): 18-22C is optimal (Adams et al., 2001) with half the fruit being seedless for a Tad of 26C or 14C. Peet et al. (1998) find fruit set is near zero for Tad above 29C (using 32C and 26C for the diurnal temperature range). However, a recovery period can cause fruit set to rebound after roughly a dozen days (Sato et al., 2000).

Poor quality tomatoes develop for Tmax <20C with Tmin <10C. Sunscald can be a problem for fruits exposed to sun in combination with heat and any kind of water stress. Since most processing tomatoes are mechanically harvested and water is cut off to fields two to four weeks prior to harvest so that equipment can operate, sunscald can reduce yield and quality of canning tomatoes.

High humidity (http://vric.ucdavis.edu/veg_info/tomatodisease.htm) can foster certain foliar diseases, such as bacterial spot (for night temperatures above 16C, and day temperatures above 20C), late blight (RH>90% when 15.5C<T<25.5C), powdery mildew (with ‘mild’ temperatures).

Table 10 Conditions that impact tomato production

Variable	Threshold or range	Comment
Growing season (frost free)	42-90d	After transplanting or seedling emergence
Average Daily Temperature (Tad)	18C (64F) < T < 22C (72F)	Optimal daytime high growing range
	>26C or <14C; ≥29C	Half of fruit do not set; no fruit set for Tad ≥ 29C (32C/26C diurnal range)
Night minimum T (Tmin)	Tmin <0C (32F)	Leaf temperature could be less than air temperature causing leaf ‘burning’ from frost for temperatures >0C.
	Tmin >13C (55F)	Minimum for adequate fruit set
Soil temperature (Tsoil)	Tsoil ≥20C	For germination; seedling vigor
Day maximum T (Tmax)	Tmax >40C (104F)	Pollination fails. Plant can survive with sufficient soil moisture.
	24C (75F) < Tmax < 34C (93F)	Optimal daytime high growing range
Relative humidity (RH)	‘high’ (>50%)	Some foliar diseases amplified
Precipitation	Drought exceeding 7-14 days	Heat during drought (or when irrigation withheld 2-4 weeks just before harvest) may cause sunscald
	Excessive	Skin splitting & rot. Foliar diseases

		promoted. Mechanical harvester cannot operate.

2.11 Deciduous Tree Fruits (stone and pome)

Stone and pome fruits are two large categories of deciduous temperate zone fruit trees. Stone fruits include apricot, cherry, peach, plum, and interspecific hybrids (e.g.pluots). Pome fruits include apple, Asian pear, and European pear. All are deciduous flowering trees that are bee pollinated. Winter dormancy is broken by a period of sufficient warmth (e.g. Whiting, et al., 2015) as estimated by a metric like growing degree days, GDD. GDD equals accumulated degrees of Tad above a base temperature. The fruits develop by a period of cell division (~30d for stone; 35-45d for pome, e.g. Warrington et al., 1999) followed by cell expansion. In stone fruits there is a hiatus between the two phases that is not present in pome fruits (Corelli-Grappadelli and Lakso, 2004). GDD is sometimes used to estimate growing season while others (e.g. Day et al., 2008) find growing degree hours (between 7C and 35C) in the first 30 days after peak bloom (GDH30) a better predictor of harvest date. GDH formulae are in Anderson et al. (1986). Water requirements vary with the weather and hence the location. To illustrate, apricots in California's Central Valley need a meter (~8 mm/day) over the growing season, but two thirds that amount (Norton and Coates, 2012) along the cool coastline. Apples, cherries, and pears need a 100d frost free period; peaches at least 120d; plums at least 140d (Hatfield et al., 2008).

Insufficient chilling hours cause inadequate, irregular, extended, and/or aborted bloom. CH are often quoted as hours between 0C and 7C, but hours between 7C and 13C can also contribute to accumulated hours of dormancy for some cultivars. Hours between 0 and 7C are used here. As with grapes, additional hours beyond the minimum can better synchronize or concentrate the bloom period. CH requirements vary greatly, for example: 'Anna' apple requires 200 hours; 'Fuji' and 'Gala' apple require 500 hours; and 'Northern Spy' requires 1000 hours below 7C. Other pome fruit examples include: 'Shinseiki' Asian pear (250h), 'Comice' pear (600h), and 'D'Anjou' pear (800h). Similar large ranges occur for various stone fruit cultivars, for example: 'Desert Gold' peach (200h), 'Santa Rosa' plum (300h), 'Blenheim' apricot (400h), 'Montmorency' sour cherry (500h), 'Elberta' peach (600h), 'Bing' cherry and 'Harcot' apricot (700h), 'Utah Giant' cherry (800h), and 'Reliance' peach (1000h). The table below uses ranges modified from Hatfield et al. (2008) based on primary US cultivars (e.g. Norton and Coates, 2012).

To initiate dormancy (endodormancy) a period of sustained cool or cold temperatures are needed that develop strong cold hardiness in buds. Large swings in temperatures instead of sustained and slow decrease in temperature result in much less cold hardiness in the same plant. Hence, beyond the variation in cultivars, management practices, and type of fruit, the weather itself influences the cold hardiness (e.g. Proebsting 1982; Salazar-Gutiérrez et al., 2016; Longstroth, 2012). The table shows ranges in Hatfield et al. (2008) but in colder growing regions (e.g. Michigan) well acclimated *trees* withstand: -35C for apple; -32C for apricot; -26C for cherry (sweet); -25C for peach (see Clements, 2014). Though as with citrus, duration increases damage risk. Dormant *buds* can withstand similar cold temperatures, e.g. -34C for cherry and -

21C for peach (Proebsting, 1982). However, the temperature required to damage buds may vary by as much as 6C because of differences in plant acclimatization (see Clements, 2014). Rodrigo (2000) has a review of how freezing can injure deciduous fruit trees flowers. Drawing on work reported by Washington State and Michigan Universities, Longstroth (2012) summarizes temperatures causing 10% and 90% kill at nine stages ranging from the earliest bud break stage until post bloom; the temperature tolerance varies with the stage as well as the tree fruit and are summarized in the table. Physiological time spent in each stage varies with the cultivar and species; for apples using a base temperature of 6.1C, Chaves et al. (2017) show each stage lasting from 20-60C GDD (or 4-30d). The nascent fruit are also vulnerable to temperatures of -1 to -2C in the one to two weeks after blooming. Hence, due to the higher sensitivity to cold, it is useful to emphasize the 1-2 month time period from initial flowering until two weeks after.

The spring of 2012 illustrates how that sensitive time period can be critical to crop success. Starting on 11 March, an extreme heat wave spread over the north central US. The unusually warm temperatures persisted for roughly three weeks. (Minimum temperatures in Bainbridge Center, Michigan remained above freezing during this event.) The accumulated GDD were enough so that stone and pome fruit trees broke dormancy and began to flower more than a month earlier than normal (mid to late March). When temperatures returned to near normal values, including Tmin swings below -2C, nascent fruit and blossoms were killed causing catastrophic yield loss. Hence *the destruction was caused by near-normal conditions*; the extreme event accelerated the physiological time resulting in vulnerable crops.

Stone and pome fruit flowers are bee-pollinated; if temperatures are too cool (Tmax <10C; Esch, 1976) bees don’t fly and won’t fly far for Tmax <13C (55F).

During summer, overnight minimum temperatures can be too warm. Warm nights during very hot summer days cause problems for the crop in the *following* year, such as: doubling in cherries. Daily average temperatures Tad >20-24 C) cause >20% of heat stressed peaches and nectarines do develop deep troughs on the fruit suture line the next year (DeJong, 2011, personal communication). Southwick and Uyemoto (1999) note that doubling increases for Tad>22-25C during bud formation (shortly after fruit are picked) in summer months, with higher temperatures associated with doubling and lower with deep sutures. A threshold for active cooling measures is temperatures >35C during flower bud formation. Doubling rate varies with cherry cultivars being high for ‘Bing’ and low for ‘Rainier’ (Micke et al., 1983). General rates of doubling in cherries are time dependent, being 5% doubling at: T>40C for 3h, or 38-40CF for 10h, 35.5-38C for 37h, or 30-35C for 100h. In Washington, heat caused up to 30% of cherries to double in 2004 and 2005.

Peaches are most sensitive to higher temperatures in the early and late stages of fruit development (DeJong, 2015) when cell division is dominant. Lopez et al. (2011) show that higher temperatures (as low as 25-30C) in the first 30 days after peak bloom accelerate fruit development but the tree cannot meet the extra demand resulting in smaller fruit size at harvest. DeJong (2015) reviews how GDH30>7000 (<6000) causes small (large) fruit at harvest. Similar GDH30 ranges apply for nectarines and plums.

Apples are also affected by high temperatures during the 1-2 months after bloom when cell division is the dominant process. Tromp (1997) noted that higher temperatures post-anthesis led to more rapid early fruit development but that later maturation was not so sensitive to high temperature. Perry et al. (1987) examine eight variations on GDD calculation and two variants of

GDH using five different base temperatures (4.4-15.6C) and five different maximum temperatures (18.3-29.4C) over four time periods (30-60days) and find no obvious favorite for predicting harvest date. Calderón-Zavala et al. (2004) show that 6mm diameter fruit grow more rapidly with high (33/28C day/night) temperatures, but such temperatures are detrimental for later stages (11mm and 18mm) i.e. 7-21d after anthesis. Cooler temperatures (19/14C) were optimal and fruits of 27mm size were insensitive to their temperature combinations. The combination 12/7C did poorly at all diameters. Expansion for Tad ~20C is an order of magnitude faster than for Tad ~6C (Warrington et al., 1999) and fruits developing in warmer temperatures after anthesis were heavier but lower quality.

Sunburn in pome fruits (sunscald in stone fruits) can occur when the skin (bark) temperatures are excessive. Such blemishes can be the main cause of unsaleable fruit (WSU-TFREC, 2017). Sunburn necrosis (browning) occurs when apple skin temperatures (Tsk) reach 52C (46-49C) according to Shrader et al. (2003). While solar radiant intensity, wind, and other factors matter, Shrader et al. link sunburn to air temperature as follows, Tsk remained below 46C when Tmax<30C; for 30C≤Tmax≤35C wind and humidity combinations might keep Tsk<46C; but Tmax>35C resulted in Tsk>45C.

High temperatures (>35-40C) inhibit anthocyanin pigments and hence fruit quality in apples (Curry, 1997) and pears (Steyn et al., 2005). The response may occur to make the fruit more reflective and less susceptible to sunburn (Steyn et al., 2009). However, elevated night temperatures encourage the pigment loss, though much of the loss can be regained by even a single cool night (Lin-Wang et al., 2011).

Other considerations about high temperatures follow. Very hot days can cause pit burn in apricots. In plums and prunes, DeCeault and Polito (2010) estimate that Tmax>27C during bloom reduces pollination with total failure above 35C. High temperatures are often associated with drought. Peaches tolerate drought well at the cell division stage, but fruit size is most affected during cell expansion (Génard and Huguet, 1996)

Precipitation prevents pollination since bees are not flying. After color develops in the fruit, rain absorption through the skin can lead to swelling and cracking of cherries, nectarines, and other stone fruits. Such cracking in cherries can be the main cause of unsaleable fruit (WSU-TFREC, 2017). Wet conditions during growth encourage diseases. Sufficiently large hail, especially during early fruit development can create nicks that expand with the growing fruit reducing marketability; also wounds may be created on branches that allow entry of diseases. There can be poor fertilization for dry conditions during pollination as happens when low relative humidity (RH<30%) accompanies California wind events.

Table 11 Atmospheric conditions that impact stone and pome fruit production

Variable	Threshold or range	Comment
Chilling hours (below 7C or between 0-7C)	>200-1600h; >700-1000h; >400-1200h;	Apple; Apricot; Cherry;

	>200-1000h; >250-1500h; >300-1200h	Peach; Pear (Asian and European); Plum.
Growing season (frost free)	60 to >100d; 90 to >100d; 90 to >120d; 90 to >140d	Cherries, Apples and pears; peaches; plums. (values adjusted from Hatfield et al., 2008)
Base temperature (Tb) for growing stage estimates	Tb=6.1C(43F); 7C(44.5F); 7.5C(45.5F)	Base temperature for apples GDD; peach GDD; peach GDH;
Tad (with Tmax-Tmin=5C) during growing season	Tad <6-15C (43-59F); >25C(77F);	Reduced yield for these Tad in: first 1-2 months for apple (varies with cultivar); in first month for peaches
Minimum T (Tmin) when plant fully dormant	-46C(-50F) to -4C(25F); -29C(-20F) to -1C(30F); -29C(-20F) to 4C(39F); -35C(-31F) to -1C(30F); -29C(-20F) to 4C(39F);	Apple; cherry; peach; pear (Asian and European); plum. Tolerated when plant is dormant, varies widely between species, cultivars, and acclimatization (Hatfield et al., 2008, ranges).
Tmin at first swelling or opening of the bud for 10% to 90% kill (30 min exposure when cold acclimated)	-9C(15F) to -17C(2F); -9C(15F) to -18C(0F) -8C(17F) to -15C(5F); -8C(18F) to -17C(1F); -9C(15F) to -18C(0F); -10C(14F) to -18C(0F)	Apple; apricot; cherry (sweet); peach; pear; plum (European) (Details in Longstroth, 2012)
Tmin at first showing of color (leaf or flower) for 10% to 90% kill (30 min exposure when cold acclimated)	-8C(18F) to -12C(10F); -5.5C(22F) to -13C(9F) -4C(25F) to -10C(14F); -5C(23F) to -13C(9F); -4C(25F) to -7C(19F); -7C(20F) to -14C(7F)	Apple; apricot; cherry (sweet); peach; pear; plum (European) (Details in Longstroth, 2012)
Tmin while blooming for 10% to 90% kill (30 min exposure when cold acclimated)	-2C(28F) to -4C(25F); -3C(27F) to -5.5C(22F) -2C(28F) to -4C(25F); -3C(27F) to -4C(24F); -2C(28F) to -4C(24F); -2C(28F) to -5C(23F)	Apple; apricot; cherry (sweet); peach; pear; plum (European) (Details in Longstroth, 2012)

	Tmin <0C (32F); -2C (28F)	Damages new growth; significant yield reduction
	Tmin<10C (15-20C); <5C (15-20C); >30C	pollen tube growth and germination poor below or above (optimal in) these values in: apple; apricot (Milatovic et al., 2016); sweet cherry (Hedhly et al., 2003)
Daytime temperature	T <10C(50F) or T >45C(113F)	Bees do not fly to pollinate
Day maximum T (Tmax)	Tmax >35C (95F)	Yields decline. Pollination fails in prunes. Sunburn of apple or pear exposed to sunlight occurs (depending on conditions occurs for 5C lower).
	Tcrit =38.5C (101F)	Critical temperature for peach
High temperatures (T) + duration (example)	T =40C (104F) for 3h	(During bud formation) increases doubling in cherries 5% the next year.
Low relative humidity (RH)	RH <30%	Pollination reduction due to dry conditions
Precipitation (P)	Drought	Important during cell expansion stage of development
	P >1mm/d	During flowering, bees don’t fly
	Excessive (depends on acclimatization)	Maturing fruit skin absorbs water, splits and rots, especially if after drought.
Hail	>1cm	Damage to nascent fruit expands with fruit, damage to branches provides entry for pathogens

2.12 Deciduous tree nuts (almond, pistachio, Persian walnut)

Tree nuts include almonds, hazelnuts, macadamias, pecans, pistachios, and walnuts. (Only ‘Persian’ or ‘English’ walnuts, *Juglans regia* are considered here, not black walnuts *Juglans nigra*.) For the past two decades, the top three tree nuts in US crop value have been almonds, walnuts, and pistachios, so these deciduous trees are the focus here. Almond trees are bee pollinated while pistachios and walnuts are wind pollinated. About 2 million acres are in tree nut production (about 1% of the US agricultural area) producing about $2B in sales (2012 data). Most of these three tree nuts (>95% of US production of each) are grown in California using close spacing that requires irrigation. The yield responds well to much irrigation during the summer fruit development. The amount of water needed varies with the climate, soil type and orchard floor management. For example, ‘Chandler’ walnuts grown in the California San Joaquin valley need 1-1.5m per year, mainly during the summer. But this assumes no water that reaches the soil surface evaporates, runs off, sinks below the root line, etc. (Goldhamer, 1998) typically the water applied is 1.5 to 2 times this amount. Almonds and pistachios need at least 180d frost free period; walnuts at least 100d (Hatfield et al., 2008). Formation of these tree nuts is similar to stone fruits in having three broad stages after fertilization: rapid hull and shell growth; shell hardening and kernel growth; kernel transformation (carbohydrates converted to proteins and fats).

Insufficient chilling hours cause inadequate, irregular, extended, and/or aborted bloom. CH is often quoted as hours between 0C and 7C, but hours between 7C and 13C can also contribute to accumulated hours of dormancy for some cultivars. Hours between 0 and 7C are used here. As with stone fruits, additional hours beyond the minimum can be effective at better synchronizing or concentrating the bloom period. CH requirements vary greatly. The table below uses ranges modified from Hatfield et al. (2008) based on the primary nut-growing region: California. Almonds need 100-500h of chilling (Hatfield et al., 2008). Ferguson et al. (2005) conclude that pistachios need ~900h of chilling; furthermore, the 1977-8 winter had only ~670h and subsequently bloom was unsynchronized, leaves deformed, and yields lowered. There are low-chill (600h) pistachios (CRFG, 1997) and some require much more chilling (~1500h). Pistachios are dioecious, meaning male trees are needed to pollinate nut-producing female trees. A second concern for pistachios is the male trees may not bloom in sync with the female trees when there is insufficient chilling, resulting in a higher number of ‘blanks’ (shells with no nut inside). Aslamarz et al. (2009) find 700-1000h for common commercial walnut varieties ‘Serr’ and ‘Hartley’. ‘Tulare’ walnuts in California’s southern Central Valley reportedly had an extended and erratic bloom period in 2015 symptomatic of too little chilling, unlike trees in the slightly cooler northern Central Valley (Beede, 2015). Chilling hours in the primary California nut growing regions have declined (Luedeling et al., 2009) and are of particular concern for future pistachio production.

Strong cold hardiness in buds develops over a period of sustained cold temperatures. Cold tolerance in walnuts is inversely linked to plant tissue water content (WC); and WC declines during autumn to a winter minimum, then rises in the spring. Thus, in winter, walnut buds are hardy to -18.5C, while wood and bark were more hardy (-23 and -31C); become less hardy by spring, so that at bud break: buds were hardy to -5C while wood and bark were hardy to -10C (Charrier et al., 2013). Cold tolerance in almonds dips to -25C in winter but is much less at anthesis. Hosseinpour et al. (2017) find at full bloom commercial varieties can tolerate -1 to -3C temperatures; Miranda et al. (2005) discuss thresholds at other bud-to-full-flowering phases, similar to peach. Dormant pistachio buds are uninjured to -9C to -10C in winter, but less tolerant when blooming. Pakkish et al. (2011) discuss bud-to-full-flowering phases and find at full bloom commercial varieties can tolerate -1 to -4C temperatures without pollination failure. Warming temperatures from late winter to spring decrease cold hardiness (e.g. walnut; Aslamarz et al., 2010). Hence, beyond the variation in cultivars, management practices, and type of fruit, the weather itself influences the cold hardiness. After sufficient chilling is reached, the time to bud break decreases rapidly (roughly halving for each 5C rise from 5 to 20C) with increasing Tad (Charrier et al., 2011).

Like stone and pome fruits, late spring frosts can reduce fruit set by damaging flowers or young nuts (e.g. Winter et al., 2009). Also like deciduous tree fruits, bud break to nascent fruit is accelerated by warmer temperatures. Hence, a climatic event where a late winter heat wave (extreme for the date) is followed by near-normal but sub-freezing temperatures can be devastating, even if the cold is not ‘extreme’ for the date.

The critical minimum temperature during pollination is ~14.5C (Karim et al., 2011) for almond; ~6.5C (5-8C depending on cultivar) for pistachio (Acar and Kakani, 2010). The minimum temperature for walnuts during pollination is 14-16C (Luza et al., 1987) with later blooming varieties needing higher temperatures.

The critical maximum temperature during pollination is ~44C (Karim et al., 2011) for almond and ~41C (40-45C depending on cultivar) for pistachio (Acar and Kakani, 2010). Pistachios thrive in hot (e.g. Tad=35C) temperatures and can withstand very high temperatures (e.g. Tmax=48C). The maximum temperature for walnuts during pollination is 37-40C (Luza et al., 1987).

Walnuts prefer annual mean temperatures between 7C and 21C. Unusual cool (e.g. monthly mean temperature of 16C) during the early spring and summer lowers walnut yields while unusual warmth (e.g. summer mean temperature of 23C) during the vegetative growing season (spring through summer) amplifies walnut yield (Winter et al., 2009).

Almond doubling is reduced by warmer temperatures prior to anthesis (Egea and Burgos, 1995).Walnuts have separate male and female flowers on the same tree, higher temperatures after bud swelling can lead to the males being less in sync with the female flowers. Cool summer temperatures tend to increase the fraction of shriveled nuts.

Sunburn in walnuts can occur when the maximum air temperatures exceed 38C (Olsen, 2006) along with ‘ambering’ and shriveling of kernels. Sunburn in walnuts is heightened by water stress such as by dry farming them in the southern Central Valley of California, though shaded nuts are much less affected (Ramos et al., 1978).

Pistachios and almonds are naturally ‘drought tolerant’ but yields decline (smaller nuts) with drought stress amplified by close spacing, soil type, etc. Almonds, being related to stone fruit, tolerate drought well at the cell division stage, but nut size is most affected during cell expansion. Almond yield is sensitive to water stress from flowering through nut development, but dry conditions are helpful later, after hull split, to dry the nutshell and avoid moisture-related pathogens. During kernel-filling, almond yield can recover from drought (as measured by water application at 20% of the tree usage) in about two weeks after soil moisture is restored (Romero et al., 2004). In pistachios, lack of soil moisture ~1 month prior to harvest reduces the split percentage (split nuts being much more valuable). Because pistachio shells and hulls split naturally, the tree is grown in regions where relative humidity is low in summer through harvest because the nut is susceptible to various pathogens like molds.

Water stress can occur if the plant is over-watered or under-watered. The plant stress can be measured in mid-day stem water potential (SWP) deficit which has units of pressure; -4≤SWP≤-6 bars is optimal for walnut vegetative growth. These SWP values occur for temperatures between T/RH=75F/40% and 100F/20%; once sized, kernel transition is fine to -8bars (e.g. 115F/20% for fully irrigated trees (Fulton et al., 2014). Each bar of SWP under or over the optimal range results in a 10% yield loss, if sustained. Almond leaves have a much larger range of SWP, though the temperature and humidity combinations that produce SWP deficit differ resulting in similar T/RH preferences as walnut. For example, almond vegetative growth is optimal for -6≤SWP≤-14bars; these SWP values occur for temperatures between

T/RH=75F/50% and 115F/20%; and during hull split higher stress -14≤SWP≤-18bars can help control some diseases (Fulton et al., 2014).

Almond flowers are bee-pollinated; if temperatures are too cool (Tmax <10C; 50F; Esch, 1976) bees don't fly and won't fly far for Tmax <13C (55F). Precipitation blocks pollination since bees are not flying.

Almond trees are shallow-rooted, so blow downs are common in young trees if the soil is saturated as may occur during a series of powerful winter frontal cyclones. In December 2002, 31m/s winds in Glenn County California caused tree blow downs (>30% of trees in some orchards; Krueger, 2004). Bees do not fly in strong winds which disrupts almond pollination. Winds may be accompanied by low relative humidity resulting in desiccation of pollen in almonds. Pistachios are harvested by shaking onto tarps. Windfall pistachio nuts are not harvestable, unlike almonds and walnuts which have closed shells.

Table 12 Atmospheric conditions that impact almond, pistachio, and (Persian) walnut production

Variable	Threshold or range	Comment
Chilling hours (below 7C or between 0-7C)	>200-1600h; >700-1000h; >400-1200h;	Almond; (most commercial types 250-500h) Pistachio; Walnut (most commercial types 650-1000h; Aslamarz et al., 2009)
Base temperature (Tb) for anthesis stages estimates	Tb=2-9C(45.5F); 4.5C(40F)	Base temperature for almond (varies with cultivar); pistachio and walnut GDH
Frost free period	>180d; >140d	Almond and pistachio (Hatfield, et al., 2008); black walnut (Baughman and Vogt, 1996)
Average daily temperature (Tad) during growing season; annual average temperature (Tann)	Tad <15C (59F) >35C(95F); Tad <25C (77F) >36C(97F); Tann <7C (45F) >21C(70F);	Reduced yield for these Tad in first 1-2 months after flowering in almond; in pistachio; walnut (annual average temperatures) but Tad=27-32C near harvest is optimal.
Minimum T (Tmin) when dormant	-10C(14F); -18.5C(-1F) to -31C(-24F)	Almond and pistachio (Hatfield et al., 2008); walnut (bud to bark)
Tmin at first swelling or opening of the bud for 10% to 90% kill (30 min exposure when cold acclimated)	-6.6C(20F) to -15.4C(4F); -5C(23F) to -15C(5F); -5C(23F)	Almond (Stage B in Miranda et al., 2005); pistachio; walnut

Tmin at first showing of color for 10% to 90% kill (30 min exposure when cold acclimated)	-3C(26F) to -10C(14F); -4C(25F) to -12C(10F)	Almond (Stage D in Miranda et al., 2005); pistachio (green tip)
Tmin while blooming for 10% to 90% kill (30 min exposure when cold acclimated)	-1(30F) to -3C(26F); -1(30F) to -4C(25F)	Almond (Hosseinpour et al., 2017); pistachio
	Tmin <0C (32F); -1.5C (29F)	Damages new growth; young fruits in almond (Hosseinpour et al., 2017)
	Tmax =14.5C; 6.5C	pollen tube growth and germination halts below this value in: almond; pistachio
Daytime temperature	T <10C(50F) or T >45C(113F)	Bees do not fly to pollinate almond
Day maximum T (Tmax)	Tmax >38C (100F)	Yields decline. Sunburn of walnut husk exposed to sunlight, darkened kernels.
	Tmax >48C (118F)	Critical temperature for pistachio
	Tmax =44C; 40-41C	pollen tube growth and germination halts above this value in: almond; pistachio
High relative humidity (RH)	RH >40%	Pistachio pathogen risk once hulls split
Precipitation (P)	Drought P <0.5m during growing season	Important during cell expansion stage of development in first 1-2 months after flowering. Almonds develop smaller size.
	P >1mm/d	During flowering of almonds as bees don’t fly in rain. During walnut anthesis blight is encouraged
Wind speed	>8 m/s	Bees may not fly to pollinate almond, pistachio nuts lost by windfall
	>20 m/s	Significant blow downs of young almond trees, when soil very wet

2.13 Wheat

Wheat is a major US grain crop ranking third among agricultural products value and fourth in tonnage. There are different categories of wheat divisible as winter varieties sown in the fall to overwinter versus spring-planted varieties. Consequently, extreme events impact these categories in different seasons. Grown widely, most wheat is produced in the central and northern high plains with significant production in eastern Washington (Hatfield et al., 2014). Hatfield et al. (2008) state the optimal Tad during vegetative growth to be 20-30C, though the optimum temperature range for grain yield is much lower: Tmax/Tmin=15/10C to 18/13C (Chowdhury and Wardlaw, 1978) because as temperatures increase, the rate of kernel development accelerates (e.g. Calderini et al, 1999). Yield appears to be optimal for Tmax/Tmin near 21/16C for spring ripening and Tmax/Tmin near 18/13C for late summer ripening (Chowdhury and Wardlaw, 1978). In the northern states wheat needs 46-53cm of water per growing season (Hagood and Nelson, 1966) however, where wheat is grown in hotter climates 48-95cm are needed (Ouda et al., 2016).

Wheat tolerance to cold varies greatly during the growth stages. Wheat can germinate when soil temperatures are as low as 2-3C (Bedi and Basra, 1993). For winter wheat, the sensitivity is as follows according to Sproyer et al. (1995) assuming the temperatures (Tmin2) last for at least 2 hours. Wheat injury occurs below these Tmin2 values during these stages: just sprouted: -17C±1C; just emerged from the soil: -11C±2C; for the remainder of tillering resistance increases to a midwinter extreme of: -22C±1C (-21C according to Wheeler et al., 2015); then decreases to the start of jointing: -4C±3C; in boot (an early development stage of the flower head): -2C±1C (-4C; Wheeler et al.); in bloom: -1C±1C; during ripening: -2C±1C. The most sensitive stages are during flower formation (heading) and flowering, where freeze-induced sterility can destroy the whole crop (Wheeler et al., 2015). Wheeler et al. summarize chilling damage, frost-related damage at different stages, and air/canopy temperatures during cold events. Zabihi-e-Mahmoodabad et al. (2011) find that cold stress: 0-12C delays germination, makes the timing uneven, and slows growth.

The plant is most susceptible to heat during booting and anthesis (flowering) with possibly a more heat-tolerant period in between (e.g. Barber et al., 2017, and references therein). High temperatures tend to decrease the reproductive period (flowering) and the grain filling period (e.g. Lawlor and Mitchell, 2000). Tashiro and Wardlaw (1990) find that Tmax/Tmin of 36/31C for just a few days prior to flowering causes pollination to be greatly reduced and fertilized kernels to be undersized. Prasad and Djanaguiraman (2014) find that short hot episodes of 2 and 5 days centered 8 days prior to bud break reduce flower fertility by 70 – 80%; hot episodes had max/min temperatures of 35/25C. Grain weight is somewhat reduced for those grains that survive, though mean daily temperatures of 35C for 5 days are sufficient at the start of heading to kill the crop. Longer duration of such hot episodes, up to a month caused declines of grain weight up to 50%. Elevating only the nighttime temperatures also decreases yield (Garcia et al., 2016). For example, Prasad et al. (2008) find nighttime temperatures that say above 20C decrease fertility and grain size. The critical temperature, Tcrit in the literature varies from 22-27C; the limiting temperature ranges 31-40C (tabulated in Deryng et al., 2014).

The length of time in the growth stages is related to the accumulation of ‘heat units’ defined as an accumulation of the daily average of the maximum plus minimum temperature. Hence hotter temperatures shorten this process in addition to lowering fertility (resulting in fewer, though possibly larger grains). Post anthesis, wheat has greater tolerance for heat; but heat accelerates the development and is typically accompanied by drought and both reduce yield where wheat is grown as rainfed agriculture. Alternatively, heat after the kernel has developed can be beneficial in drying the grain prior to harvest.

Drought causes many impacts on the nutrient and yield properties of wheat, as reviewed by Nezhadahmadi et al. (2013). They also summarize the sensitivity to drought of wheat at different growth stages. Early season drought has far less impact than later in the growth cycle. Yield is most strongly affected when flower structures and pollen are forming. Drought during the grain-filling period reduces yield nearly as much. Drought tolerance varies as some plants have better 'drought avoidance' (deeper roots, etc.) or 'dehydration tolerance' (withstanding higher partial dehydration). Since wheat is often grown in a Mediterranean climate zone, where there is often late growing season drought, some example drought studies are illustrative. Termination of precipitation/irrigation from well-watered fields beginning 69 to 10 days before flowering resulting in a 63% to 14% reduction in yield (Fischer and Maurer, 1978). In a test of drought (rainfed only;) and stressed (27% of rainfed at heading and later) conditions to an irrigated control, Guinta et al. (1993) find reductions in all grain properties (yield, number of grains, grain weight, etc.) proportional to the water deficit below the adjacent irrigated plots; triticale (a wheat-rye hybrid) tolerated much better the lowered water availability. When drought delivered half the water delivered by irrigation, the yield was half, the additional water reduction for the stressed plants had a proportionally larger reduction in yield.

Flooding increases diseases and causes oxygen depletion though wheat can generally withstand flooding for a day. Davies and Hillman (1988) show a 25-50% reduction in yield for wheat flooded for 3 days and 50-75% reduction in yield for 7 days flooding, in both cases over every two week cycle. The yield reduction was from reduced ear number and grain size (weight, etc.) and less from grain number per ear. In a Mediterranean climate most rain falls in winter, so flooding of winter wheat fields if more likely. Dickin and Wright (2008) examine sustained (>40 days) waterlogging (and summer drought) on wheat for several winter periods and find yield reductions of 20-25%. However, Cannell et al. (1980) find smaller yield losses because the plant can compensate somewhat in later stages; however, wheat is most sensitive to waterlogging after germination but before emergence.

Changnon. (1971) finds a minimum size of 6.4mm diameter to cause damage to wheat and the amount of damage is proportional to the number of hailstones.

Table 13 Conditions that impact wheat production

Variable	Threshold or range	Comment
Soil Temperature (Tsoil)	Tsoil ≥4C (40F); Tsoil ≥10C(50F)	Minimum thresholds: for any seed germination; for full germination possible
Low Average Daily Temperature (Tad)	0C(32F) < Tad <12C(54F)	Growth slowed, some pathogens enhanced, yield declines rapidly for colder Tad
High Tad	Tad >27C (81F)	Yields decline depending on plant growth stage timing (Tcrit)
	Tad >40C (104F); >35C(95F)	Crop failure by a single day (Tlim); by 5 days at start of heading.

Minimum T (Tmin2) thresholds for 2 hours at these extremes	-17C (2F); -11C (12F); -21C(-6F); -4C(24F); -2C(28F); -1C(30F)	Severe damage varies with stages: sprouting; emergence; winter maximum resistance; early jointing; late jointing and booting; heading, flowering, and grain filling.
Nightime Tmin increases	Tmin >20C (68F)	Decrease in fertility, grain size. Yield reduced at warmer temperatures.
Air temperature	0C(32F)<T<10C(50F)	Chilling damage if prolonged
Precipitation (P)	Drought	Yield declines most strongly after booting and is proportional to fraction of optimal soil moisture. Effect amplified by Tad above optimal range
	Excessive	Fosters pathogens; sustained waterlogging reduces yield. Wheat tolerates 1 day submerged.
Hail size	size>6.4mm	Leaf destruction, depends on number.

3. CONCLUSIONS

From the perspective of a climate modeler, it would be convenient if major agricultural commodities had well-defined thresholds of model variable extreme values beyond which damage or yield declines could be pegged. This chapter should make clear that such thresholds are often imprecise. The thresholds have ranges due to the variation among cultivars and the conditions the plant experiences over time. With that big caveat, some general comments can be made.

Cold hardiness in perennial crops is related to how the acclimatization to cold occurred; sustained cold develops greater cold tolerance. The variability in the cold affects the dormant period needed by deciduous perennial crops like tree nuts and grapes, and insufficient dormancy disrupts flowering and pollination lowering yields. Winter wheat is also grown in regions where insulation by snow is expected during winter, so that when snow is absent the damage by near-normal cold is greater as happened in 2014 and 2015.

Daily minimum temperature, Tmin can have effects for high and low values. Impactful ranges vary with the commodity. Some plants need T > Tmin (rice, cotton); some need nightly recovery T < Tmin. Animals can tolerate higher daytime temperatures on successive days if they have cool enough nighttime temperatures to recover. Bee pollination requires temperatures above 10C (and <45C) without rain.

For many crops, there is an impactful threshold near freezing. Freezing (or just below) is often a key threshold: at blossom (vegetable and tree crops), seedling (vegetables) and harvest (citrus). Freeze after an unusual period of warmth that initiates plant development such as bud break to blooming and nascent fruit formation can be particularly impactful (e.g. Gu et al., 2008) and it remains a possibility in the presence of a warming world (Cannel and Smith, 1986; Meehl et al., 2000). As shown for tree fruits in 2012, catastrophic destruction was caused by near-normal conditions that followed an extreme event for the time of year. The temperatures were not extreme in an absolute sense, being well below 35C, but they were warm enough to greatly accelerate the physiological time resulting in vulnerable crops. This situation is particularly impactful for tree fruits and nuts as management options are limited unlike annuals for which planting can be delayed or repeated.

Animals and crops are affected by high temperatures, too. Daily maximum temperature, Tmax, extreme thresholds are often near 35C(95F) to 40C(104F). Higher plant T stresses plants, especially by limiting recovery and growth at night. Lobell et al. (2013) show a strong negative yield response in Maize to accumulation of temperatures above 30 °C (or extreme degree days, EDD). Maize is a thirsty crop and the water demand doubles as temperatures increase from 27 to 35C (Lobell et al., 2013).

Duration of higher and lower temperatures matters. For cold, that duration might be measured in hours while for high temperatures it may be measured in hours to days. Two days in a row are more severe than one day.

Humidity matters: Low RH (<30%) can: dry wine grapes, shatter rice, stress ornamentals. Tw or Td thresholds (high T & RH combinations) vary with the commodity. Such combinations determine the heat stress tolerated by livestock

Excessive Precipitation disrupts scheduled field operations (sowing, harvesting) as happened for soybean in 2008 and maize and soybean in 1993. Some field crops can withstand flooding for a few days, but otherwise, flooding causes catastrophic losses, cosmetic damage, and heightens pest pressure. When combined with high temperatures splitting and spoilage can occur before harvest (e.g. tomatoes, cherries)

Drought (not remediated by irrigation) impacts perennials (like strawberries and tree crops) as well as annual field crops. A common associated effect is higher summer Tmax; yields diminish as higher temperatures drive demand for more water that is not there. Examples are maize and soybean in 1988 and 2012, winter wheat in 1989, and maize in 2002. In areas of irrigated agriculture, drought leaves insufficient water for irrigation or frost protection (e.g. citrus, grapes).

High winds can blow down plants (lodging of rice, soybean, and wheat) or drop the crop to the ground (pistachios). If accompanied by wet conditions, shallow rooted trees (almonds) may blow down.

In summary, plants and animals respond to conditions over time. An extreme event can be short but have impacts that are expressed during ‘normal’ conditions or sustained long after the event occurs.

Table 14 Impacts from different extreme weather

Average daily temperature (Tad)	
	Lowered yield (lack of growth or death) outside optimal (acceptable) ranges.
	Impacts crop phenology including development of: sufficient dormancy, vegetative and the fruit growth stages
Daily minimum temperature (Tmin): high or low; range varies with commodity	
	Some plants need overnight T> Tmin threshold (rice, cotton)
	Some crops and animals during a heat wave need nightly recovery T< Tmin
	Freezing (or just below) often a key threshold: at blossom (tree crops), seedling (vegetables) & harvest (citrus)
High daily Tmax: typically >35C (95F) to 40C (104F), varies with commodity	
	The impact on yield can be very different depending on when it occurs during the growth cycle. Often, worst at just before flowering through nascent ‘fruit’ stage.
	Longer duration of higher temperatures matters
	Exceeds maximum developmental temperature
	Higher Tmax stresses plants, especially if recovery and growth at night are limited
	Sunburn of pome fruits and walnuts
Relative humidity (RH) and T	
	High Tmax with low RH: (<30%) dried wine grapes, (<20%) shattered rice, stressed ornamentals
	High Tmax with high RH: exceed level of heat stress tolerated by livestock, or plant to cool its leaves and fruit, foster development of certain pathogens
High winds	

	Blow down and dropping harvest on ground: pistachios, rice & other grains
	If accompanied by wet conditions, blow down of shallow rooted trees (almonds)
Excessive precipitation	
	Disrupts scheduled field operations (sowing, harvesting)
	Flooded field crops cause crop loss, cosmetic, and pest issues
	When temperatures also high cause splitting and spoilage (tomatoes, cherries)
Drought	
	Perennials (strawberries, tree crops) more susceptible than annual field crops due to limited crop choice or management options
	Associated effects of higher summer Tmax, amplify the loss
	Insufficient water for irrigation or frost protection

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