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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. Agricultural products have vast diversity. Many commodities are not covered. Some are skipped because the environment is highly managed (e.g. poultry).

This chapter is motivated to help climate modelers interpret impacts in their output. A statistical quantity like TX95, the 95th percentile value of daily maximum temperature, often has little bearing on what impacts agricultural products. Climate literature has more relevant but still basic quantities[163]. This chapter collects a nuanced set of extreme weather conditions that impact crops.

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 contradicts a longer term average.

There are mortality thresholds and dormancy thresholds. *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 general climate science literature; but timing is critical. The critical timing is keyed to *phenological* stages 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 these 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.

Phenology refers to crop development stages. Developmental temperature thresholds exist, such as a temperature below which development stops. For example, banana plants go dormant below ~18C; 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 calculated different ways[171,134,50] (http://fruitsandnuts.ucdavis.edu/Weather_Services/chilling_accumulation_models/about_chilling_units/) but generally are cumulative hours during winter months below a threshold (e.g. 7C) and often above a lower value (e.g. 1C) and hours above 7C may be added or subtracted based on the method used. 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 matters as 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. until a GDH threshold is reached). Fruit drop early in the season can diminish yield irreversibly for the year. Other crops (e.g. soybean) can re-bloom and recover some yield. 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 tissues (like a limb). Alternatively, soft tissues (like tomato leaves) exposed to clear night skies can be harmed during temperatures above freezing. 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 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 sometimes 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 Tmax[169] 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 trends[39].

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[130].

An extreme of temperature may be amplified by the moisture present, either too much humidity (so the plant or animal is inefficient at cooling by transpiration) or too little humidity (so pollen viability is shortened). 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[41]). 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: plant temperature can be higher (lower) than air temperature[70], by up to 10C, if the plant is stressed (or not)[21].

Despite these caveats, one can spot extreme event impacts on yield as illustrated in Figure 1.

2. COMMIDITY GROUPINGS

2.1 Citrus

Citrus is a tropical or subtropical fruit tree. 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. California is the primary producer of table oranges in the US. Average daily temperatures (Tad) for development[101] are in Table 1. However, 6-12 weeks of cold (T<10C) or drought-induced dormancy create a flush of blooms after dormancy ends and synchronizes later fruit ripening. Various combinations of factors affect bloom efficiency and fruit set[99].

Low temperatures are a primary limiter of US citrus production. A 2007 freeze affecting California caused $800M losses to the state's citrus industry. Mature trees tolerate slightly colder temperatures due to cold hardening[99] and having larger branches. Ice formation in citrus tissues causes the damage; 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 can be worse than a half hour at -4C. In oranges: 4 hours at -7C kills 1 cm (3/8 inch) or smaller wood, while T< -2C for 12 continuous hours kills 5cm (2 inch) limbs and possibly the entire tree. 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). Growers extend the temperature range by applying water (releasing latent heat as it freezes).

High temperature, especially with strong solar radiation and low humidity can cause severe wilting, even with adequate soil moisture. Since transpiration cannot keep leaves cool, yield declines if the situation persists. Sunscald also occurs.

Drought amplifies fruit drop both of young and mature fruit. Water needs vary with temperature and humidity, but California orchards 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[37]), Greasy spot (relative humidity: RH>90%, especially during summer).

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[72]. Together, beef and dairy account for more than a quarter of all US agricultural value. California, the leading state for dairy production, has ~1.8M dairy cows, many populating the southern San Joaquin valley. This region has hot, dry summers, so heat stress is likely. Heat-stressed cows go off feed and stop milk production. During the 2006 heat wave and for weeks after, milk production suffered, totaling >$95M in losses. During the event 30,000 cows died (10% mortality) in part because temperatures did not cool sufficiently at night and cows could not recover from extreme daytime temperatures.

Being mammals, cattle must maintain a core temperature in a narrow range. 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 combining temperature and relative humidity stress is the temperature-humidity index (THI, Figure 2) having several definitions[3,62]. THI is adapted from the discomfort index[165] which uses wet and dry bulb air temperatures. If relative humidity is high, THI increases and animals are less able to cool by panting. THI is more relevant for heat stress. THI is used to define the associated livestock weather safety index (LWSI). Alternatively, CCI[97], which 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 in Table 2. CCI ranges from -44.1 to 67.7. CCI is more broadly applicable than THI for assessing cold conditions. For dairy cattle, T=20-22C is 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 non-acclimated animals or CCI< -20 for animals that have acclimated to cold[97].

Excessive heat with high humidity creates high stress. THI values between 74 and 79 are considered dangerous, with values >84 indicating an emergency situation[4]. THI>90 (e.g. T=45C, RH=25%) leads to: 20% drop in milk production, aborted fetuses, and reproductive cycle interrupted for weeks afterward. Lactating cows are more vulnerable, having >1C higher core temperature[15] than heifers for air temperatures >30C. THI >98 is considered 'fatal' to cows but this ignores factors like duration above thresholds, solar radiation, and coat color[57] which amplify the problem or wind which can reduce the problem[97]. Considering duration, THI is often interpreted[61] in terms of hours times degrees above a threshold like THI=84; the purpose being to estimate the animal's core temperature. As little as 3 THI-hours/day for 3 days[67] is considered severe if nighttime THI values do not dip below 72 for >2 hours. Other metrics[97] are used like black globe temperature.

2.3 Field Fruits (strawberries and cucurbits)

Commercial strawberries are an herbaceous, perennial, subtropical plant. About 80% of the US crop is grown in two California regions, depending on the time of year. Florida has much of the remaining production. Strawberries like cool conditions (Table 3). Plants respond to diurnal solar radiation and temperature; if temperatures became uniformly warmer over a year, there would be earlier fruiting but less overall yield[127].

Strawberries are most sensitive to frosts and freezes during and just after bloom, including if the leaf or flower surface temperature drops below 0C (air temperature could be warmer). Mature fruit tolerate 1-2C colder. If cooling is gradual, plants may tolerate Tmin of -6C. 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 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 diseases[172] are 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, Angular leaf spot (daytime T~20C).

Cucurbits include watermelon, cantaloupe, honeydew, cucumbers, and squashes. These vining, tropical annuals 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 inhibit bee flight.

Melons can tolerate maximum temperatures up to 45C for muskmelon[10] but 32C for watermelon[49]. Drought (or insufficient irrigation) can significantly reduce yield as can water applied a week before harvest[69].

Temperatures below 4C injure squash and cucumbers while temperatures above 29C cause flowers and undersized fruit to drop.

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

Many vegetables (Table 4) are annual row crops. Leaf crops, Cole crops, and other vegetables are generally very sensitive to extremes: especially 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 for germination, yield, and growth are cool[71].

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 and Tmin ~7C. Freezing damages outer leaves making the plant more susceptible to diseases. Lettuce is generally sensitive to high temperatures though sensitivity varies between varieties. For iceberg lettuce temperatures >25C accompanied by >8 hours sunlight cause early bolting (flower stalk and seed production) before the head has reached full size. Iceberg lettuce is grown[167] where nighttime temperatures are 3-12C and daytime temperatures 17-28C. Germination is optimal for 20-25C but inhibited or impossible[142] above 30C without priming. Lettuce requires a lot of water over the crop cycle; 1.5 to 3 times the needed amount is applied depending on the irrigation method[167]. Spinach tolerates a wider range of temperatures than lettuce. Spinach seeds geminate between 2-30C, though 7-24C is optimal[84]. Temperatures of 15-18C produce optimal growth though there is some growth down to 5C and up to 30C. Bolting is prompted by longer day lengths and temperatures above 23C. Mature spinach plants survive temperatures[84] down to -9C. The water needs are 1/4 to 1/3 those of lettuce.

Broccoli tolerates a wider temperature range than cauliflower. Broccoli seeds geminate between 4-35C, though 7-24C is optimal[83]. Mean temperatures of 18-20C produce optimal growth. Broccoli (cauliflower) grow with temperatures from 4-35C (3-29C) though growth slows outside the optimal range[89]. For temperatures ≥27C, cauliflower heads develop undesirable properties. Frost damages seedling and young plants; mature plants tolerate temperatures to -5C. The water needs are similar to those of iceberg lettuce, though cauliflower needs more water 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) if nights are cool[140] (e.g. 18C). 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) than their relative, tomatoes, with increasing damage (dependent on duration) for colder temperatures. Some potato varieties tolerate colder conditions or acclimate to them, but not all[125]. Potato varieties have wide variation in drought tolerance[147].

Carrot foliage tolerates some frost, however, for T<10C foliage and root grow slowly. Optimal taste and color develop for temperatures between 18-21C (15.5≤Tad≤18C); undesired flavors develop[121] for air temperatures above 30C. Seeds germinate in soil temperatures from 4C to 35C, but optimally from 15-29C.

2.5 Grapes

Grapes are a temperate climate perennial vine subdivided into three production categories: table grapes, raisins, wine grapes. Wine grapes are grown under cool to warm growing season average temperatures (Tgsa). Table grapes are grown from warm to hot conditions, while raisins are grown where drying is fostered at hot Tgsa. Table grapes include muscadines (adapted to southeastern US conditions) and concord (adapted to the US northeast). Plant leaves do well[53] for daytime temperatures from 20C to 32C (Table 5). Sunny warm days promote the vine's physiological processes, sugar content, and ripening while cool nights retain acidity; these primary characteristics are manipulated by a winemaker.

Grapes need a period of winter dormancy, CH with temperatures *below* 10C, though 1-7C is used to calculate CH. The CH sum may be reset to zero by several days above 10C. Higher values of CH are desired to improve the synchronization of bud break once temperatures are sustained above 10C when grapes become physiologically active[175].

Flowering needs 17≤Tgsa≤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 >4000.

Freezes 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) accelerates bud break making a subsequent frost devastating.

High temperatures impede grape development. For example, Semillon grapevines exposed to a simulated heat wave (Tmax=40C, Tmin=25C) at different growth stages, stopped growing during veraison (developing grape color) and mid-ripening, taking a dozen days to recover[60]. Thompson seedless[98] 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[157] wine grapes. 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[106]. Timing relative to mid-season thinning matters; an extreme July heat wave made up time lost by delayed bud break from the cool spring during 2006 in California. Hot, dry, and windy conditions near harvest can dry wine grapes like raisins, cause sunburn, and shrink harvest period, as happened in 2008.

Precipitation has multiple effects. Too much rain in spring disrupts regular deficit irrigation resulting in too much vegetative growth. Rain during pollination inhibits fruit set (such conditions in 1996 reduced fruit set 25% in California). 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. Most of the water demand (~70% of the total) is from fruit set to harvest.

2.6 Maize

Maize (or 'corn') is a tropical annual grass that holds the number one value and tonnage of US crops. Most maize is grown in the 'Corn Belt' region from the northern Ohio River valley across to the northern high plains[72].

Maize is sensitive to minimum temperatures near freezing. The plant is damaged by $-2 \le T \le 0$C, but might survive; temperatures below -2C kill the plant[119]. Germination requires a minimum[153] soil temperature (Table 6). Cold tolerance depends on moisture content and variety, but none survive[68] -10C. Significant differences[78] in development occur between maize lines for a 2C reduction in temperature (Tmax/Tmin of 15/13C vs 17/13C). Cold periods can foster diseases[48].

Increasing temperature shortens the period of grain-filling which leads to smaller grains and yield[8]. While maize survives brief Tmax>45C with adequate soil moisture, such high temperatures cause lasting yield decline. Yields increase up to a critical temperature (Tc=29C) above which yield rapidly declines as temperature increases but at a nonlinear rate[149]. (E.g. replacing one day at 29C with 40C causes a 7% yield decline.) Pollen loses viability at temperatures above either 38C[75] or 36C[46]. No fertilization occurs when exposed to four hours at 40C[46]. Kernel development rate rapidly declines[31] for temperatures rising from 30C to 35C. Mismatched hormonal changes[28] 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[33]. A night/day temperature range of 35/40C produced less than half the yield of a 20/25C range[31]. A 'failure point temperature' of 35C was estimated[71] by averaging prior studies, including the temperature effects at endosperm division stage. Estimated thresholds[164] for damage (Tcrit) and for 'maximum impact' (Tlim) for daytime temperatures are Tcrit/Tlim = 35/45C. Estimates[44] 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 affects growth[91]. High heat is often associated with drought[41]. Temperature increase with precipitation (P) deficit effects[141] vary (positive or negative yield changes) depending on when the drought or high temperatures occurred relative to anthesis. For maximum temperatures above 29C, yield declined no matter when a rainfall deficit of 2.5cm occurred. P<4.5cm/8d creates 1.2-3.2% decline[173] 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. A Tmax of 40.6C could cause a 14% decline from normal for a 2.5cm drought. Higher declines in yield for these Tmax or P values happen from 5 weeks before to 2 weeks after flowering with the biggest decline about two weeks before flowering[141].

Excessive rainfall (>1m in the growing season[161]) can foster pathogens, stunt growth (due to saturated soils), cause erosion, and/or inhibit mechanical operations at critical times (like harvest). In flooding conditions, yields decline though vegetative parts survive submergence[136] ~2 days if conditions are warm, ~4 days if temperatures are cool.

Hail can also damage crops[123], though each event usually does not cover a large area. 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[25]. While the plant may survive, injury to the growing point may result in abnormal growth and a total loss[81].

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 housed. Greenhouse growers manipulate Tmax and Tmin to adjust crop development for marketing purposes (e.g. so 'Easter' lilies start blooming just before Easter Sunday). Extreme events disrupt such timing (Table 7).

Outdoor nurseries are partly controlled environments. Some protective measures can be taken to protect frost-sensitive plants to a Tmin of -2C (28F). However, cosmetic damage is 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. Cold damage is amplified when a preceding warm period prompts a flush of highly sensitive new foliage. A threshold generally used to indicate total loss of frost-sensitive crops is -3C.

Generally, Tmax>32C is a threshold for foliage/yield loss, while several hours above 38C 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). Greenhouses using evaporative cooling are up to 11C 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. The National Greenhouse Manufacturers Association specifies that design plans use winds of at least 31m/s. Accumulations of snow can collapse shade, lathe, and greenhouses. Hail can break greenhouse rigid panels (glass or plastic) or puncture plastic film. Outside, hail causes plant trauma. A May 2011 hail storm caused a 30% loss of bedding plants in Sacramento California.

2.8 Rice

Rice is a major annual grain crop requiring a long frost-free period to develop. Arkansas and California are the primary US producers. With many cultivars suited to a range of tastes and climates, the sensitivity to temperatures varies markedly among cultivars. Table 8 summarizes broad generalizations.

Rice needs warm temperatures. Below 20C the percentage of blanks increases (from 12 to 50%) 60-75d after planting (early into 'heading'). Cooler temperatures slow maturation and 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 by 10% for each 1C that Tmin>33C. Rice is most sensitive during pollination. Heat tolerance varies with rice genotype[79]. Too hot (Tmax ≥ 38-41C depending on duration[145]) during the short period (a few hours) during which fertilization occurs causes near sterility in most commercial cultivars. Fertility declines for Tmax>32C[18].

Drought can inhibit any phase, but drought early during 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 can be a problem in California. The rice grain dries during daytime then rehydrates at night. Cracking may arise if rice dries out too much during the hot part of the day (say to 16% moisture content) then reabsorbs water during the higher nighttime humidity (back to say, >20%). When milled, that cracked seed shatters and is unsaleable.

High wind speeds (WS>20m/s) create multiple problems. Wind may cause extensive lodging (grain stalks blown to the ground) during harvest (after field water removal). Wind can often be accompanied by low RH. In October 2004, the rice growing region of California experienced WS>40kph 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%.

2.9 Soybean

Soybean is an annual legume that ranks third in US crops and livestock tonnage. Widely planted, soybean is most concentrated in nearly the same region[72] as the ‘Corn Belt’. Vegetative growth (e.g. leaf area index) increases but photosynthetic rate is essentially constant[21] for air temperatures of 26, 31, and 36C. The optimal harvest index is near Tad=26C corresponding to Tmax/Tmin=32/22C[17] though seed size declines for Tad>22C. Other studies[16,154] find Tad near 23C (Tmax/Tmin=26/20C) optimal (Table 9).

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[148].

Cold temperatures at or below -2C kill soybeans; frost at higher temperatures is damaging[119]. There is no vegetative growth for Tad below 6C prior to flowering[61]. Pollination fails[144] below 13C. Seeds risk chilling injury for soil temperatures below 16C while germination fails due to imbibition (swelling by liquid water uptake) with soil temperatures <5C[88].

Soybean tolerates higher temperatures than rice. Vegetative growth is not limited by temperature as much as is seed formation[16]. Pollen viability declines for (instantaneous) temperatures >30C to fail at 47C[144]. Yield declines rapidly for average daily temperatures (Tad) above 31C (i.e. Tmax/Tmin=36/26C) leading to declining productivity until reaching crop failure for Tad=39C (i.e. Tmax/Tmin >44/34C[17]). Yields increase up to a critical temperature (Tcrit=30C) above which yield rapidly declines as temperature increases[149] but at a nonlinear rate. Estimates of Critical and limiting average daily temperatures estimates are: Tcrit=35C and Tlim=40C[164]; Tcrit=34-35C and Tlim=40C[44]; Tcrit=39-40C[18].

The plants use water most rapidly during the reproductive stages, especially from full bloom to pod filling stages[80] reaching 8mm/d for example, in Kansas growing conditions[138]. Excessive precipitation may cause excessive vegetative growth and lodging (laying on the ground). In flooding conditions, plants can survive submergence for 2-4 days[151,160] though young plants submerged in warm conditions are more at risk. Disease pressure increases with time under water.

Hailstones >6.4mm diameter cause damage[25] to soybean, more in early summer (May-June) than later (July-August) all else being equal. Damage before and during the first two weeks of flowering can be reduced by the plant developing new flowers.

2.10 Tomato

Tomatoes are a tropical vining plant. California leads US production of processing tomatoes (https://www.cdfa.ca.gov/Statistics/PDFs/2016Report.pdf). Commercial tomatoes grown in California are irrigated (78% with buried drip in 2012; http://apps.cdfa.ca.gov/frep/docs/Tomato_Production_CA.pdf). Plants are determinate (one fruit set) or indeterminate (continuous fruit production).

Tomatoes are adversely affected by low temperatures (Table 10). Light frosts cause defoliation. Even when temperatures are a few degrees above freezing, clear nighttime skies with light winds can allow leaf temperatures to cool enough to be damaged. Soil temperature must be >20C for seeds to germinate and for plants to have vigor. However, transplants are common, exceeding 30% of planted acreage in California. Cool soil and air temperatures promote *Verticillium* wilt (http://ipm.ucanr.edu/PMG/r783100911.html). The plant needs Tmin>13C for fruit to set. Poor quality tomatoes develop for Tmax<20C with Tmin<10C.

Tomatoes have high temperature limitations. Plants suspend forming new fruits or abort development of nascent fruits at high Tmax. Pollination fails for Tmax>40C though the plant survives with adequate water. Fruit set is near zero for Tad>29C (using 32C and 26C for the diurnal temperature range[128]). However, a recovery period can cause fruit set to rebound after roughly a dozen days[146].

Sunscald occurs for fruits exposed to sunshine in combination with heat and water stress. Since most processing tomatoes are mechanically harvested and water is cut off to fields two to three weeks prior to harvest, sunscald reduces 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 >16C, and day temperatures >20C), late blight (RH>90% when 15.5C<T<25.5C), powdery mildew (with ‘mild’ temperatures).

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 (like pluots). Pome fruits include: apple, Asian pear, and European pear. Winter dormancy is broken by a period of sufficient warmth[174] as estimated by metrics 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[170]) followed by cell expansion. Stone fruits have a hiatus between the two phases unlike pome fruits[32]. GDD is sometimes used to estimate growing season length while others[40,5] find growing degree hours (between 7C and 35C) in the first 30 days after peak bloom (GDH30) a better predictor of harvest date. 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[120] along the cool coastline.

Insufficient chilling hours cause inadequate, irregular, extended, and/or aborted bloom. Hours between 7C and 13C can also contribute to accumulated CH dormancy for some cultivars. As with grapes, additional hours beyond the minimum can better synchronize or concentrate the bloom period. CH requirements vary greatly[71,77,120] as Table 11 shows.

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 variation in cultivars, management practices, and type of fruit, the weather itself influences cold hardiness development[93,132,143]. The table shows ranges, 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[30]. As with citrus, duration increases damage risk. Dormant *buds* can withstand similar cold temperatures[132], e.g. -34C for cherry and -21C for peach. Temperatures able to damage buds may vary by as much as 6C because of differences in plant acclimatization[30]. How freezing injures deciduous fruit trees flowers has been reviewed[137] including 10% and 90% kill at nine stages[93] ranging from the earliest bud break stage until post bloom. Physiological time spent in each stage varies with the cultivar and species; for apples using a base temperature of 6.1C, each stage lasts from 20-60C GDD[24] (or 4-30d). The nascent fruit are 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 may dictate crop success. Starting on 11 March, an extreme heat wave spread over the northern central US. The unusually warm temperatures persisted for roughly three weeks. (Bainbridge Center, Michigan remained above freezing during this event.) The accumulated GDD were enough so stone and pome fruit trees broke dormancy and began flowering more than a month earlier than normal. When temperatures returned to near-normal values, including Tmin swings below -2C, nascent fruit and blossoms were killed causing catastrophic crop 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) bees don't fly[51] and won't fly far for Tmax<13C.

During summer, overnight minimum temperatures can be too warm. Warm nights during very hot summer days cause problems in the *following* year, such as: cherry doubling (two fruits from one flower). 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[156]. Doubling rate varies with cherry cultivars[102] being high for 'Bing' and low for 'Rainier'. In Washington, heat caused up to 30% of cherries to double in 2004 and 2005. Daily Tad>20-24 C cause >20% of heat stressed peaches and nectarines to develop deep troughs on the fruit suture line the next year. A threshold for active cooling measures is temperatures >35C during flower bud formation.

Peaches are most sensitive[43] to higher temperatures during early fruit development (and also late in late maturing varieties). Higher temperatures (as low as 25-30C in the first 30 days after peak bloom) accelerate fruit development[94] but the tree cannot meet the extra demand resulting in smaller fruit size at harvest.

Apples are also affected by high temperatures during the 1-2 months after bloom when cell division is the dominant process. Higher temperatures post-anthesis lead to more rapid early fruit development but later maturation is not so sensitive[166] to high temperature. A study[129] examining 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) finds no obvious favorite for predicting harvest date. Fruit diameter matters[20]: 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) are optimal while the combination 12/7C did poorly at all diameters[20]. Expansion for Tad~20C is an order of magnitude faster[170] than for Tad~6C and fruits developing in warmer temperatures after anthesis are heavier but lower quality.

Sunburn in pome fruits (sunscald in stone fruits) occurs when the skin (bark) temperatures are excessive. Such blemishes can be the main cause of unsaleable fruit[177]. Sunburn browning (necrosis) occurs when apple skin temperatures, Tsk reach 46-49C (52C)[150]. Solar radiant intensity, wind, and other factors influence Tsk. One study[150] links sunburn to air temperature as follows: Tsk remained <46C when Tmax<30C; for 30C≤Tmax≤35C wind and humidity combinations might keep Tsk<46C; but Tmax>35C resulted in Tsk≥46C.

High temperatures (>35-40C) inhibit anthocyanin pigments and fruit quality suffers in apples[36] and pears[158]. The response may occur to make the fruit more reflective and less susceptible to sunburn[158]. Elevated night temperatures encourage pigment loss, but much pigment can be regained by even a single cool night[90]. Very hot days can cause pit burn in apricots. In plums and prunes, Tmax>27C during bloom reduces pollination[42] 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[58].

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. Cracking in cherries can be the main cause of unsaleable fruit[178]. 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 hail may create wounds 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.

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

Tree nuts include almonds, hazelnuts, macadamias, pecans, pistachios, and walnuts. ('Persian' or 'English' walnuts, *Juglans regia* are discussed, not black walnuts *Juglans nigra*.) The top three tree nuts in US crop value are almonds, walnuts, and pistachios. Almond trees are bee pollinated while pistachios and walnuts are wind pollinated. These tree nuts are mainly grown in California (>95% of US production of each) using irrigation during nut development. The water needed varies with the climate, soil type and orchard floor management. 'Chandler' walnuts grown in the San Joaquin valley need 1-1.5m per year, mostly in summer. Typically, 1.5 to 2 times this amount[59] is applied because water reaching the soil surface evaporates, runs off, or sinks below the root line. 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. Hours between 7C and 13C can accumulate CH dormancy for some cultivars. Like stone fruits, hours beyond the minimum improve synchronizing or concentrating the bloom period. CH requirements vary greatly. Table 12 uses ranges based on California's primary nut-growing regions. Pistachios may need ~900h of chilling[52]. The 1977-8 winter had only ~670h and subsequently the: bloom was unsynchronized, leaves deformed, and yields lowered. There are low-chill[34] (600h) pistachios and some require much more chilling (~1500h). Pistachios are dioecious, meaning male trees are needed to pollinate nut-producing female trees. Another concern for pistachios is male trees may not bloom in sync with female trees when there is insufficient chilling, resulting in a higher number of 'blanks' (shells with no nut inside). Commercial walnut varieties 'Serr' and 'Hartley' need 700-1000h[7]. 'Tulare' walnuts in California's southern Central Valley had an extended and erratic bloom period in 2015 symptomatic of too little chilling, unlike trees in the slightly cooler northern Central Valley[14]. CH in the primary California nut growing regions have declined[95] raising concerns 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 are more hardy (-23 and -31C). Hardiness decreases by spring[27], so that at bud break: buds are hardy to -5C while wood and bark are hardy to -10C. Cold tolerance in almonds dips to -25C in winter but is much less at anthesis. At full bloom commercial varieties can tolerate -1 to -3C temperatures[76]; thresholds at other bud-to-full-flowering phases[103] are similar to peach. Dormant pistachio buds are uninjured to -10C in winter, but less tolerant when blooming. At full bloom, commercial varieties can tolerate -1 to -4C temperatures[126] without pollination failure. Warming temperatures from late winter to spring decrease cold hardiness (e.g. walnut[6]). 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[26].

Late spring frosts can reduce nut set by damaging flowers or young nuts[176]. Bud break to nascent fruit is accelerated by warmer temperatures. Like tree fruit, a late winter heat wave (extreme for the date) 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 for almond[155]; ~6.5C (5-8C depending on cultivar) for pistachio[1]. The minimum temperature for walnuts[96] during pollination is 14-16C with later blooming varieties needing higher temperatures.

The critical maximum temperature during pollination is ~44C for almond[155] and ~41C (40-45C depending on cultivar) for pistachio[1]. Pistachios thrive in hot (e.g. Tad=35C) temperatures and can withstand very high temperatures (e.g. Tmax=48C). The maximum temperature for walnuts[96] during pollination is 37-40C.

Walnuts prefer annual mean temperatures between 7C and 21C. Unusual cool (e.g. 16C monthly mean temperature) during the early spring and summer lowers walnut yield while unusual warmth (e.g. mean temperature of 23C) during the vegetative growing season (spring through summer) amplifies walnut yield[176].

Almond doubling (two kernels in one shell) is reduced by warmer temperatures prior to anthesis[47]. Walnuts have separate male and female flowers on the same tree; higher temperatures after bud swelling can lead to male being less in sync with 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 along with 'ambering' and shriveling of kernels[122]. Sunburn in walnuts is heightened by water stress, though shaded nuts are much less affected[133].

Pistachios and almonds are naturally 'drought tolerant' but yields decline (smaller nuts) with drought stress amplified from close spacing or other factors. 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[139]. In pistachios, lack of soil moisture ~1 month prior to harvest reduces the split percentage (split nuts being much more valuable). Because the shells and hulls split naturally, pistachios are grown in regions with low relative humidity in summer through harvest because the exposed nut is susceptible to pathogens like molds.

Water stress occurs if the plant is over-watered or under-watered. Plant stress can be measured by mid-day stem water potential (SWP) deficit which has units of pressure; $-4 \leq SWP \leq -6$ 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[55]. 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 $-6 \leq SWP \leq -14$bars; these SWP values occur for combinations between T/RH=75F/50% and 115F/20%; and during hull split higher stress $-14 \leq SWP \leq -18$bars can help control some diseases[55].

Almond flowers are bee-pollinated; if temperatures are too cool (Tmax <10C[51]) bees don't fly and won't fly far for Tmax <13C. 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 >30% of the trees in some orchards[85] to blow down. Bees do not fly in strong winds which disrupts almond pollination. Winds may be accompanied by low relative humidity resulting in desiccation of almond pollen. Pistachios are harvested by shaking onto tarps. Windfall pistachio nuts are not harvestable, unlike almonds and walnuts which have closed shells.

2.13 Wheat

Wheat is a grain crop ranking third among US agricultural products value and fourth in tonnage. Wheat categories divide into winter varieties sown in the fall to overwinter versus spring-planted varieties. Extreme events impact these categories in different seasons. Most wheat is produced in the central and northern high plains with significant production also in eastern Washington[72]. Optimal temperature range[29] for yield is much lower than the optimal range for vegetative growth[71] because as temperatures increase, the rate of kernel development accelerates[19].

Wheat tolerance to cold varies greatly during the growth stages. Wheat can germinate when soil temperatures[13] are as low as 2-3C. For winter wheat, the sensitivity to cold temperatures varies greatly with the growth stage[152] as illustrated in Table 13 assuming cold temperatures (Tmin2) last for at least 2 hours. Wheat injury occurs below those Tmin2 values. Tmin2 decreases from when winter wheat just emerges from the soil through the remainder of tillering to a midwinter extreme then increases to jointing. The most sensitive stages are during flower formation (heading) and flowering, where freeze-induced sterility can destroy the whole crop. Cold stress, 0-12C, delays germination, makes the timing uneven, and slows growth[179].

The plant is most susceptible to heat during booting and anthesis with possibly a more heat-tolerant period in between[11]. High temperatures tend to decrease the reproductive period (flowering) and the grain filling period[86]. 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[162]. Short hot episodes of 2 and 5 days centered 8 days prior to bud break[130] reduce flower fertility by 70 – 80%; those 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[56]. Nighttime temperatures that stay >20C reduce fertility and grain size[131]. Published critical temperatures vary from 22-27C and limiting temperature ranges[44] are 31-40C.

The time spent in each growth stage is related to the accumulation of 'heat units' defined as an accumulation of the daily average of Tmax plus Tmin. 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 several impacts[118] on the nutrient and yield properties of wheat and the sensitivity varies with different growth stages. 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 results in a 63% to 14% reduction in yield[54]. Comparing[64] drought (rainfed only) and stressed (27% of rainfed at heading and later) conditions to an irrigated control, finds reductions in all grain properties (yield, number of grains, grain weight) proportional to the water deficit below the adjacent irrigated plots. Triticale (a wheat-rye hybrid) tolerated much better the lowered water availability. When drought provided 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. In a Mediterranean climate most rain falls in winter, so flooding of winter wheat fields is more likely, though excess summer rainfall reduces yield[168]. Yield reductions[38] were 25-50% for wheat flooded for 3 days and 50-75% 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. Sustained (>40 days) waterlogging (and summer drought) on wheat for several winter periods produced yield reductions[45] of 20-25%. However, others[23] 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.

A minimum hail size of 6.4mm diameter damages wheat[25] and the amount of damage is proportional to the number of hailstones.

3. CONCLUSIONS

It would be convenient if major agricultural commodities had well-defined thresholds of climate model variables beyond which damage or yield declines could be pegged. This chapter makes clear that such thresholds are often imprecise. The thresholds have ranges due to the variation among cultivars and the conditions each plant experiences over time. Nonetheless, some general comments are made (with examples) and summarized in Table 14.

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

Daily Tmin can have effects for high and low values. Impactful ranges vary with the commodity. Some plants need temperature above a threshold (rice, cotton); some need nightly recovery below a threshold. Animals 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, an impactful threshold is near freezing. Just below freezing (-1C) is often a key threshold: at blossom (vegetables, tree crops), seedling (vegetables) and harvest (citrus). If an unusual period of warmth initiates plant development such as bud break to blooming and nascent fruit formation, subsequent freezing can be highly impactful[63] and this scenario remains possible in a warming world[22,100]. In 2012, catastrophic destruction of tree fruits resulted from near-normal conditions that followed extreme warmth for the time of year. The warmth was not extreme in an absolute sense, being well below 35C, but warm enough to greatly accelerate the physiological time resulting in vulnerable crops. This sequence is especially 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. Daily Tmax extreme thresholds are often near 35C(95F), 40C(104F), and 45C(113F). High air temperatures stress plants, especially by limiting recovery and growth at night. Yield response in maize is strongly negative[91] to accumulation of temperatures above 30C. High Tmax is often linked to greater water usage (field crops, tree crops, cattle). Maize water demand doubles as temperatures increase[91] from 27 to 35C.

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 can: dry wine grapes, shatter rice, stress ornamentals. Wet-bulb or dew point thresholds (high T and RH combinations) vary with the commodity. Over the Midwestern US, Tmax has cooled slightly over the last century but humidity increased causing the heat index and THI to increase[62]. THI>75 (>98) stresses (kills) 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 (tomatoes, cherries)

Drought (not remedied by irrigation) impacts perennials (strawberries, tree crops) as well as annual field crops. Drier-than-normal soil encourages higher-than-normal temperature and yields diminish as those 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. For irrigated agriculture, drought leaves insufficient water for irrigation or frost protection (citrus, grapes).

High winds can blow down plants (lodging rice, soybeans, and wheat) or drop the crop to the ground (pistachios). For saturated soils, shallow rooted trees (almonds) may blow down.

In summary, plants and animals respond to complex conditions over time. Some non-extreme values of meteorological variables combine to create extreme agricultural conditions in metrics like THI (instantaneous) or GDD and CH (cumulative). To estimate those conditions requires observations and projections at high time and space resolution. Climate modelers are encouraged to output agriculture-relevant metrics or provide high time (hourly) resolution for calculating metrics from model output. An extreme event can be brief but have impacts expressed during subsequent 'normal' conditions or sustained long after the event occurs. Even in a warming world, such episodic extremes remain possible and may even become more likely.

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Service of the US Department of Agriculture accessed from the websites: https://www.nass.usda.gov/Charts_and_Maps/Field_Crops/index.php and http://usda.mannlib.cornell.edu/usda/current/htrcp/htrcp-04-13-2017.txt

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Table 1 Atmospheric conditions that impact citrus production

Variable	Threshold or range	Comment
Growing season (frost free)	>280d	From[71]
Average Daily Temperature (Tad)	Tad> 9.4C (49F) to 13C (55F); ~20C (68F); 23C (73F) < Tad < 34C (93F); 37-39C	Minimum (depends on type) for development. Roughly optimal during fruit set (but will set fruit above and below this value); Optimal range during fruit growth; limiting temperature
	>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	90-120cm	Optimal water per year[35]
	Drought	Heat during drought (or when irrigation withheld) can cause fruit drop, even tree mortality
	Excessive	Skin splitting and rot. Some foliar and root diseases promoted.

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[97]	CCI < -5 ; -44.1	Mortal cold conditions for young cattle. E.g. T= 5C, RH=80%, WS=9m/s, SR=100W/m^2 ; Lowest value considered (T = −30°C, WS = 9 m/s, SR = 100 W/m2, and RH= 80%)
	CCI < -20	Mortal cold for acclimated cattle. E.g. T= -10C, RH=20%, WS=9m/s, SR=100W/m^2
Maximum CCI[97]	CCI >37.9 ; 67.7	Severe value calculated from T = 30°C, RH = 50%, WS = 1.0 m/s, and SR = 500 W/m^2 ; Highest value considered (T = 45°C, WS = 1 m/s, SR = 900 W/m2, and RH = 80%)
Day maximum THI	THI<74; 74≤THI<79; 79≤THI≤84; 84<THI<98; THI>98	'normal'; 'alert'; 'danger'; 'emergency'; 'fatal' labels for these conditions are commonly used[66] and defined from cattle transport experience[87]
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.

Table 3 Atmospheric conditions that impact strawberry production

Variable	Threshold or range	Comment
Growing season (frost free)	~100d	From[71]
Optimal temperatures	13≤T≤21C (55-70F)	
Night minimum T (Tmin)	Tmin ≥ -6C(21F); 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) from[71]
Optimal temperatures	30≤T≤35C (86-95F); 21≤T≤29C (70-84F)	for cantaloupes; watermelons
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)
Precipitation	25-38cm	Optimal water over growing season[69]
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
Optimal temperatures	18≤Tad≤27C (64-80F) ; 16≤Tmin≤21C ; 24≤Tmax≤29C	For squashes
Precipitation	2.5 cm/week	Optimal watering in Florida[107]

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
Day length	>14 hours (with T>23-24C)	Accompanying mild or warmer temperatures leads to bolting
Optimal temperatures	12C (53F)≤Tad≤24C (75F); 24C (75F) ≤Tmax≤35C (95F),	Higher values for spinach
Precipitation (irrigation)	1m (1.5-3m);	Optimal watering of iceburg lettuce (amount applied) [167] less for leaf lettuce; spinach 1/3-1/4 this amount.
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 (81F); 35C (95F)	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); -3C (26F)	Threshold to avoid carrot; potato foliage damage; potato mortality
Soil temperature (Tsoil)	4C (39F)≤ Tsoil ≤35C (95F); Tsoil>20C (68F)	Carrot germination or potato sprouting do not occur outside this range; potato bulking suppressed[105]
Day maximum T (Tmax)	Tmax >29C (84F); 35C (95F)	Carrot; potato plant quality thresholds (if nights cool, otherwise 30C/86F)
Precipitation	2.5 cm/week	For potatoes during the later stages of tuber formation

Table 5 Atmospheric conditions that impact grape production (all types)		
Variable	Threshold or range	Comment
Chilling hours (below 7C or between 1-7C)	50-400h ; 100-150h ; >4000h ; >750h	For winter dormancy for most grapes[92]; for most commercial *vinifera* varieties; for some wild cold environment types; for good bud break synchrony
Growing season (frost free)	~100d ; >120d	American; European. From[71]
Optimal[82] daily temperature growing season average (Tgsa)	13C (55F)≤Tgsa≤21C (70F) ; 17C (63F)≤Tgsa≤22C (72F) ; Tgsa≥20C (68F) ;	Wine ; table ; raisin
Tgsa thresholds	Tgsa >20C (68F); >22C (72F)	Fruit quality reduced for wine grapes; table and raisin grapes
	Tgsa (Tb) =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)	25-75cm/growing season (90-120cm of irrigation)	Plants need most moisture from fruit set to harvest
	P < ~50cm/growing season	Drought:
	Excessive	Depending on timing: Inhibits pollination. Some foliar and root

		diseases promoted. Mature fruit skin split and rot if after drought.

Table 6 Conditions that impact maize production		
Variable	Threshold or range	Comment
Soil Temperature (Tsoil)	Tsoil≥10C (50F); Tsoil>35C (95F)	Minimum threshold for seed germination; kills seedlings[105]
Growing season (frost free)	~65 to 120d	Varies with cultivar
Average Daily Temperature (Tad)	16(61F)≤Tad≤35C (95F); 12(54F)≤Tad≤35C(95F) ; 20 (68F)≤Tad≤25C (77F)	Acceptable ranges for: germination; growth; optimal growth[71]
Low 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); >36C (97F)	Heat stress maximized; pollen viability lost
Precipitation (P)	50-80cm of water per 80-110d growing season ; 64 cm. 80-130cm per season	Optimal range[35] ; optimizes[149] yield. In hotter climates[124]
	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

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.

Table 8 Atmospheric conditions that impact rice production		
Variable	Threshold or range	Comment
Growing season (frost free) with precipitation	90-150d with 100-110cm[74]	In hotter climates 15% more water is needed[124]
Temperature (T)	10C (50F) < T < 37C (98F)	Little or no growth outside this range
High average daily T (Tad)	Tcrit >35C[164] (95F)	Critical temperature (Tcrit). Yields decline (depending on plant growth stage timing).
	Tlim >36[164], 38[9], or 36-40C[70] (97-113F)	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	Optimal range for 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

Table 9 Conditions that impact soybean production

Variable	Threshold or range	Comment
Growing season (frost free)	135-150d	From[35]
Soil Temperature (Tsoil)	Tsoil ≥4.5C (40F); Tsoil ≥10C(50F)	Minimum thresholds: for any seed germination; for full germination possible. Tsoil>35C kills seedlings[105]
Average Daily Temperature (Tad)	12(54F)≤Tad≤40C(104F) ; 23(73F)≤Tad≤32C(90F) . 22(72F)≤Tad≤24C(75F)	Growth range ; range for better production where the Tad was based on a 10C diurnal range between Tmax and Tmin[17]. Optimal yield production[71]
Low 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)	45-70cm ; 69 cm	Water per growing season[35] ; optimizes yield[149].
	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

Table 10 Conditions that impact tomato production

Variable	Threshold or range	Comment
Growing season (frost free)	42-90d	After transplanting or seedling emergence
Soil temperature (Tsoil)	Tsoil ≥20C	For germination; seedling vigor
Average Daily Temperature (Tad)	18C (64F) < Tad < 22C (72F)	Optimal growing range[2]
	>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
Day maximum T (Tmax)	25C (77F) ≤ Tmax ≤ 35C (95F)	Optimal daytime high growing range (https://anrcatalog.ucanr.edu/pdf/7228.pdf)
	Tmax >40C (104F)	Pollination fails. Plant can survive with sufficient soil moisture.
Relative humidity (RH)	‘high’ (>50%)	Some foliar diseases amplified
Precipitation	Drought exceeding 7-14 days	Heat during drought (or when irrigation withheld 2-3 weeks just before harvest) may cause sunscald
	Excessive	Skin splitting & rot. Foliar diseases promoted. Mechanical harvester cannot operate.

Table 11 Atmospheric conditions that impact stone and pome fruit production

Variable	Threshold or range	Comment
Chilling hours (below 7C or between 1-7C)	>200-1600h; >700-1000h; >400-1200h; >200-1000h; >250-1500h; >300-1200h	Apple (eg: 'Anna' 200 h, 'Pink Lady' 200-400, 'Fuji' and 'Gala' 500 h, Golden Delicious 700 h, 'Northern Spy' 1000 h below 7C.); Apricot (e.g. 'Blenheim' apricot 400h, 'Harcot' apricot 700h); Cherry (e.g. 'Montmorency' sour and 'Lapins' 500h, 'Bing' cherry 700h, 'Utah Giant' 800h); Peach (e.g. 'Desert Gold' 200h, 'Elberta' peach 600h, 'Reliance' 1000h); Pear (e.g. Asian: 'Shinseiki' 250h, European: 'Comice' 600h, 'D'Anjou' 800h); Plum (e.g. 'Santa Rosa' 300h).
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[7])
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. Tolerance varies widely between species, cultivars, and acclimatization[71].	-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.
Tmin at first swelling or opening of the bud for 10% to 90% kill (30 min exposure when cold	-9C(15F) to -17C(2F); -9C(15F) to -18C(0F) -8C(17F) to -15C(5F);	Apple; apricot; cherry (sweet);

acclimated) Details[93]	-8C(18F) to -17C(1F); -9C(15F) to -18C(0F); -10C(14F) to -18C(0F)	peach; pear; plum (European)
Tmin at first showing of color (leaf or flower) for 10% to 90% kill (30 min exposure when cold acclimated) Details[93]	-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)
Tmin while blooming for 10% to 90% kill (30 min exposure when cold acclimated) Details[93]	-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) ()
	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[104]; sweet cherry[73]
Daytime temperature	T <10C(50F) or T >45C(113F)	Bees do not fly to pollinate
High temperatures (T) + duration	T>40C for 3h, 38-40C for 10h, 35.5-38C for 37h, or 30-35C for 100h	Approximate combinations (during bud formation) increases doubling in cherries 5% the next year. (varies with cultivars)
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
Growing degree hours in	GDH30>7000 (<6000)	Tendency for small (large) fruit size at

the first 30 days (GDH30)		harvest[43]. Similar GDH30 ranges apply for nectarines and plums.
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

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

Variable	Threshold or range	Comment
Chilling hours (below 7C or between 1-7C)	>200-1600h; >700-1000h; >400-1200h;	Almond; (most commercial types[71] 250-500h) Pistachio; Walnut (most commercial types[7] 650-1000h)
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; >100d; >140d	Almond and pistachio[71] ; Persian walnut[71] ; black walnut[12]
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[71] ; 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[103]) ; 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[103]) ; 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[76] ; pistachio
	Tmin <0C (32F); -1.5C (29F)	Damages new growth; young fruits in almond[76]
	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

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
Average Daily Temperature (Tad) Optimal Tad or Tmax/Tmin	20C≤Tad≤30C ; Tmax/Tmin= 15/10C to 18/13C. Tmax/Tmin near 15/10C to 21/16C	During vegetative growth[71] ; Optimal range[29] for yield of late summer wheat during ripening. Optimal during winter wheat spring ripening[29].
Low 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[152] (approximate, ±2C)	-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.
Nighttime Tmin	Tmin >20C (68F)	Decrease in fertility, grain size. Yield reduced at warmer temperatures.
Air temperature	0C(32F)<T<10C(50F); T>32C for >8h	Chilling damage if prolonged; prolonged high T can halt vernalization[105]
Precipitation (P)	 46-53cm ; 48-95cm	water per growing season: where grown in northern states[65] where grown in hotter climates[124]
	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.

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)
	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.
High daily Tmax: typically >35C (95F) to 40C (104F), varies with commodity; 45C (113F) often a limiting (fatal) temperature	
	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 (THI thresholds of 75, 84, 98), 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

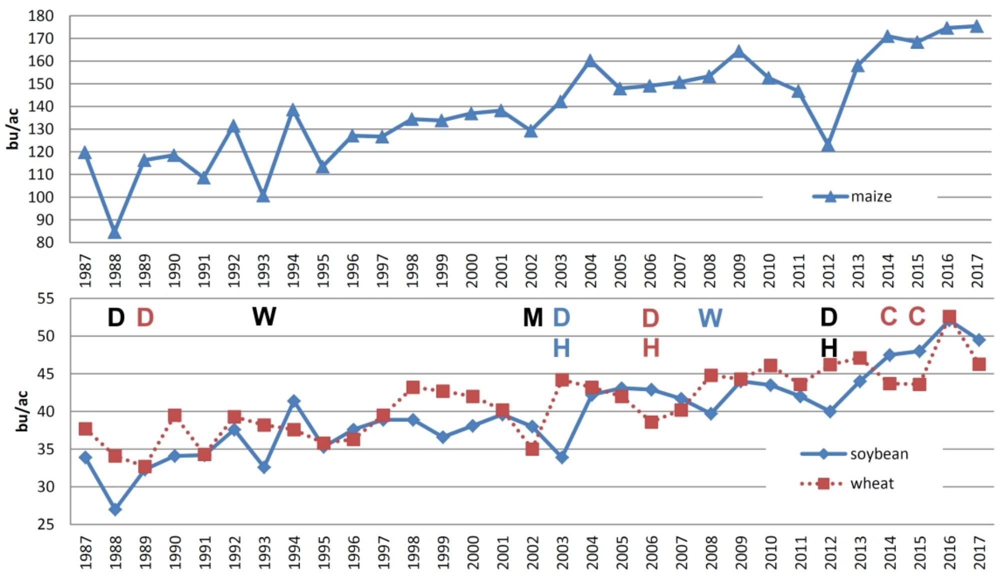

Figure 1. Average annual yields in the US for three major commodities: maize (triangles), soybean (diamonds), and wheat (all types; squares). Letters indicate the primary extreme weather: cold (C), drought (D), heat (H), mixture (M), and wet (W). Letter color: black means affects two or more crops, red 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[108]. 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[109]. 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 500 yr) rainfall[110]. 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[111] harvested since 1917. 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[112]. In 2006, a dry winter reduced winter wheat in the southern plains while a hot summer reduced spring wheat in the northern plains[113]. 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[114]. In 2012, drought and accompanying extreme high summer temperatures greatly reduced yields of maize and soybean but mainly accelerated wheat maturation[115]. Drought and higher air temperatures drive plants to transpire and deplete soil moisture more rapidly[135]. 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[116,117].

472x304mm (200 x 200 DPI)

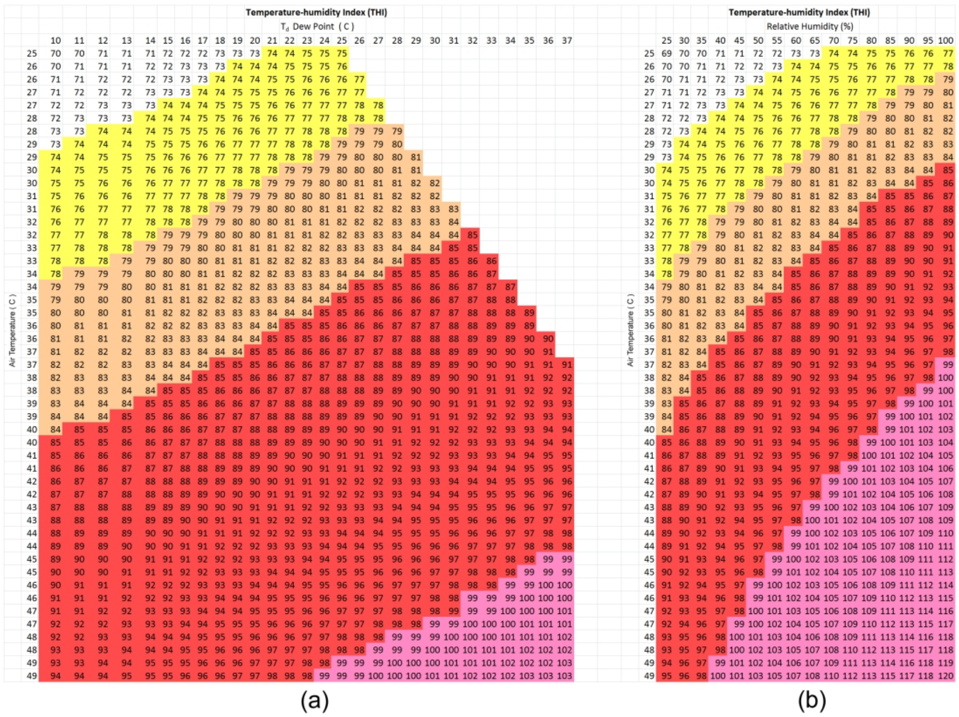

Figure 2. Temperature-humidity Index (THI) values for (a) combinations of air temperature and dew point and (b) combinations of air temperature and relative humidity. Shading indicates level of concern: yellow for 'alert', orange for 'dangerous', red for 'emergency', and pink for 'fatal' conditions for cattle.

457x330mm (150 x 150 DPI)